Bio-Inspired Unmanned Underwater Vehicle

Final Design Report

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INTRODUCTION

In nature, metachronal paddling is a form of small-scale locomotion common in many species of aquatic crustaceans. This form of movement is defined by the distinctive, wave-like pattern found in the staggered sweeping leg motion that allows many species to traverse through their environment. A wide variety of species swim using this method, most notably shrimp, prawn, and krill, among others. These species have a remarkable degree of fine control over their movements allowing for very precise motion through constrained environments. This propulsion strategy allows for quick, agile, and precise actions.

Existing research suggests that metachronal paddling differs significantly from other traditional methods of propulsion. The staggered motion of the legs creates a unique blend of forward and upward thrust. This type of paddling creates counter-rotating vortices at the ends of each adjacent leg, which in turn requires a natural phase lag between each leg to be utilized to keep the forward momentum of the animal. The phase lag between each leg is the slight delay in motion performed at a certain rate depending on the speed being travelled at. It is believed that this unorthodox form of propulsion could be adapted to modern submersible vehicles, granting them similar benefits, and improving their speed and agility.

The goal of this project is to further explore the use of metachronal paddling in nature and apply the knowledge to create a digitally controlled underwater vehicle. We have the goal of designing and building a mechanically driven system to mimic this propulsion on a larger scale and prove its benefits for the modern takes on autonomous underwater vehicles.

PROBLEM DESCRIPTION

Almost all remotely operated underwater vehicles in use today have problems with lack of speed and agility. Due to the large size of most current vessels, high speeds are not able to be reached, nor are they able to perform complex tasks that require quick turns, and advanced motion in water. In the few bio-inspired vessels that have been designed, there is an issue of the natural propulsion methods compromising the devices' ability to perform said tasks.

This project's goal is to create a remotely operated vehicle (ROV) that utilizes metachronal paddling as its primary propulsion method. In addition, there are several requirements and constraints used to frame the final design. These requirements include:

- A maximum paddling rate of ten hertz
- An ability to withstand ten feet of water pressure
- An ability to be remotely controlled
- A target battery life of thirty minutes
- A speed of up to one meter per second
- A maximum body length of one meter

The main project sponsor is Dr. Arvind Santhanakrishnan. He has had extensive research with the use of metachronal paddling in nature and is optimistic that this form of propulsion can greatly improve the performance and abilities of underwater vehicles. Our team planned weekly meetings with him to monitor our progress, as well as assist us with analysis, fabrication, and testing. He, along with the National Science Foundation's Directorate for Engineering, have provided the team with a budget of $4,000 to work with for this project.

The stakeholders of this project include the National Science Foundation's Directorate for Engineering and their CBET Program, underwater vehicle design companies, submarine technology companies, and biological research. This research project has the potential to increase the knowledge of nature-based propulsion strategies and improve the performance of autonomous underwater vehicles. This project is still in its design and research phases but could eventually be utilized for the advanced studies of oceanic and biological research.

ENGINEERING PRINCIPLES

To design and fabricate a successful prototype, there were many engineering principles, both previously acquired and new ideals that had to be considered. These engineering principles guided research, modelling, design choices, and fabrication methods chosen. The guiding engineering principles of this project include:

- Communication and collaboration
- Robust thinking
- Feasibility
- 3D design
- Mechanical design
- Fluid mechanics
- Heat transfer
- Material knowledge

Communication and collaboration came into play as this was a largely involved team project, and each member had to contribute their ideas and knowledge to be able to create the best design possible given the requirements. Robust thinking guided the team to make decisions regarding the analysis, evaluation, and possible results (including consequences) of an idea. The idea of feasibility is the understanding that this project has a tight time schedule and that the main goal is to deliver a successful prototype that functions and achieves the specifications given by the sponsor. It also includes recognizing that there is no purpose in creating a complex, impressive design if it does not work. Feasibility strongly guided the teams' time management and design decisions to be efficient and reasonable, as well as cost-effective and within budget.

When modelling the design ideas, 3D design technology such as Solidworks and FEA (Finite Element Analysis) was used to show the structural and mechanical pieces, as well as the design's capability to perform under water and under the effects of pressure and mechanical motion. Mechanical design also played into the structural design and component choices, as well as each parts' capability to perform the desired motion, propulsion, and strength requirements. Each component was fully analyzed using strength and torque calculations, as well as material capability to withstand pressure, weight, and functional wear. Material knowledge was also used in these calculations and analysis to ensure that each component was of a proper material able to withstand the forces acting on the mechanical system from the motion and effects of water. From the material choices side, waterproof materials or materials that would not rust in water were also vital to the success of our design.

Heat transfer knowledge was used to ensure that the electronic side of our system would not overheat and cause damage to other parts of the device or risk injury to others. Since electronics being used in water can cause a safety risk of electrocution, the design was required to be fully sealed. However, this caused heat by the motors, gears, and movement of parts within to be trapped inside the closed, submerged body. Further heat analysis guided the team to design a cooling system for the prototype to maximize performance and reduce the damage on individual components from heat exposure.

Lastly, fluid mechanics principles were utilized to further understand how a body fully submerged in water performs. The center of mass, center of gravity, center of buoyancy, and the centroid of the body was found to understand how the body will rest in water, as well as the angle of pitch that will occur with movement. The idea of stability and neutral buoyancy was utilized to create a device that has an appropriate weight that will be stable and neither sink nor float when fully submerged.

ENVIRONMENTAL, HEALTH, SAFETY, AND ETHICAL CONSIDERATIONS

There are many considerations and constraints that separate a good design from an approvable design. To create an appropriate, successful, and efficient design, many considerations were taken into account and utilized to ensure the safety and ethicality of the prototype.

Environmentally and ethically, this design needs to use products that are non-toxic, reusable and/or recyclable, and environmentally safe. It also needs not cause harmful emissions. Our electronic power system allows for the smallest amount of emissions possible. To ensure this, the use of batteries and non-fuel power supplies are utilized. The chosen batteries are to be rechargeable and wrapped so that battery acid does not leak out and cause damage or pollution. Even though materials in batteries are mined for, the use of rechargeable batteries still allows for the least amount of pollution for the project situation. Since the device will be used in water, it also needs to not pollute or damage the environment in which it is functioning. This influenced the materials chosen for the body and internal components. It is vital for this design to include these considerations currently so that for future models, it can be used in real-life environments without the threat of damaging any ecosystems or wildlife.

Health and safety are another set of considerations that were analyzed. Since this design is being created for research purposes, the device needs to be safe for researchers to manufacture, use and handle. A Safety Review Board will thoroughly inspect the design and all functioning aspects to ensure this. This design also needs to be safely manufacturable for our teammates. To achieve the highest level of knowledge and safety, all team members have undergone the appropriate training on all machinery and devices to be used during the fabrication process. The next consideration taken in the design phase was to ensure that no harmful chemicals or materials were used so that safe handling and manufacturing could occur. This influenced material choices, as well as waterproofing techniques for body design. Another consideration was the safety risk of using electronics in an underwater device. To avoid the risk of electrocution or electrical fire, the team became knowledgeable in the wiring and use of electronics, as well as secure waterproofing methods. This consideration led to a large knowledge acquisition for our team, as well as a deep understanding of the necessary precautions to be taken for the health and safety of the users of this prototype.

A few social, cultural, and global considerations needed to be understood to ensure a final product that was useful, efficient, and successful for the requirements of the project. Social considerations included recognizing teamwork, communication, and splitting up tasks within the group was the best way to get the job done within the time constraints. The teamwork aspect of this involved having a shared set of values and goals among the group so that everyone contributed and worked together to achieve the project requirements. Culturally and globally, the main consideration is that this prototype is to be used for research purposes for studying metachronal paddling in underwater vehicles. Another global consideration that influenced the design factors was the idea of product afterlife. The design of this project is for maintainability and research, so each component of the product can be reused or recycled for other purposes once the device has reached its maximum performance capabilities.

Since this prototype will be used in water, the idea of sustainability was another major consideration to be aware of. Water creates a lot of pressure and wear on a body, especially when submerged at different depths. Also, water can cause certain materials to rust or weaken with time. Due to this, sustainability goals influenced the design choices in materials, waterproofing methods, and component choices. The main goal is to create a successful research prototype, so it was particularly important to understand all sustainability considerations and component durability within each aspect of the design.

Due to the research purpose of this project, the professional considerations that needed to be fully understood included meeting all project requirements in the most efficient, cost-effective way possible. Also due to the nature of the project, it was important to be able to adjust and access components within the body for alterations and changes that may come with further advancements in research, components, and maintenance.

ENGINEERING CODES, STANDARDS, AND GUIDELINES

Every design has certain engineering codes and standards to abide by for environmental protection, safety purposes, maintainability, and product longevity, among others. However, due to the newer advancements of autonomous underwater vehicles, there are not many specific AUV codes and guidelines. To ensure proper design standards are met, we were able to follow different electrical codes, building and manufacturing guidelines, and safety codes.

The IEEE (Institute of Electrical and Electronics Engineers) has many codes regarding health and safety and environmental protection. IEEE 1680 is a chapter that has an environmental assessment of materials being eco-friendly, as well as codes for end-of-life action plans, life cycle extension of a product, and energy conservation. To incorporate these codes, we have designed our AUV to be made of non-toxic materials that can be scrapped or reused, as well as an assembly and disassembly guide to ensure proper care of the device and components before and after use.

The NFPA (National Fire Protection Association) 70, also known as the NEC (National Electric Code), is another set of vital codes for this project. The NFPA 70 is a section of codes that sets standards and guidelines for safe design, operation, inspection, and maintenance to protect people and buildings from electrical hazards. The specific codes that guided our electrical design included the NFPA 70A, 70B, 70E, and 78. The NFPA 70A is the national electric code, which provides the underlying guidelines for safe design, installation, and inspection. This led the team to understand how to design a safe, effective electrical supply system that can perform the necessary tasks. 70B is a guideline for safety while doing maintenance, which requires all power to be disconnected when maintenance is being performed. 70E is a set of standards for electrical safety in the workplace, requiring hazard signs, clean workspaces, and proper protective equipment and precautions to be known. This taught the team about safety equipment such as electrical gloves. 78 is a guide on safe, documented electrical inspections. This code helped guide us in preparing our wiring diagrams for the electronics to ensure safe and proper power supplies, as well as correct coloring of wires.

In researching different related codes, it was discovered that there is a German and Norwegian Society, known as the DNV*GL, who has created a solid set of standards and guidelines for ROV's. Their codes include safety regulations, environmental protection codes, operation and maintenance requirements, machinery systems, electrical systems, and equipment uses. The codes from this society that helped guide our design included section 2 1.1, 1.11, 1.12, 5.2, 6.8, and section 5 code 2. Section 2 code 1.1 states that "ROV's shall be designed and constructed in such a way that failure of any single component cannot give rise to a dangerous situation" (DNV GL 7). This inspired us to design an internal automatic shutoff in the electronics of the system so that no harmful accidents could happen to the operators of the device if high voltages occurred. Code 1.11 calls for the center of gravity to be below the center of buoyancy, which allows for the device to be neutrally or negatively buoyant so that it can stay submerged. Code 1.12 requires the devices not to be dangerous to the environment nor cause any environmental pollution. This also played into the material and component choices in the design. Code 5.2 has a table of documentation requirements, from the basic components such as weight and material selection to the test procedures and failure analysis protocols. This gave us a starting idea of all the documentation and analysis that would need to be done on the design to get it approved. Code 6.8 has required codes on electrical safety and design with relation to waterproofing and protection. These codes tie in with the NEC and NFPA codes on electrical safety and gave the team further insight into electrical hazards. Section 5 code 2 has guidelines and standards for appropriate power supplies and emergency power supply systems, as well as safety on using and maintaining appropriate power. These specific ROV codes gave a strong outline for our project and provided us with ideas to appropriately document, perform analysis and design a working, approved prototype.

KNOWLEDGE ACQUISITION

Due to the scope of the project, several different fields of knowledge had to be acquired by our team. Because we had to fabricate the full vehicle, all our members had to take several machine trainings. We took mill and lathe training, additive manufacturing, laser cutting, makerspace certification, and welding. We also made sure to have several members have the same training courses as to ensure a redundant system in case of an absence. During all training and manufacturing, the team also had to learn the operation of all appropriate protection equipment and how to handle them.

Every member of our team is a mechanical engineer. However, our project had several electronic components and computational necessities. Therefore, half of our team dedicated a large portion of their time to learning about electronics. This included how to wire batteries, circuit breakers, Arduinos, and other similar components, as well as how to create custom wiring and Y-splitters. It also required us to learn how to communicate with and create a remote-controlled vehicle. This meant we had to not only learn the LabVIEW programming language, but also Arduino IDE as we used an Arduino to send commands to onboard motors and servos as well. In the meantime, we had to utilize I2C communication to transfer said data between LabVIEW and the Arduino. On top of this, we had to learn how to send the above communication through a neutrally buoyant tether. This required a large amount of outside help and guidance from peers, professors, and graduate students.

Another major knowledge acquisition included the ideas of gear ratios and mechanical design fabrication methods. The designed locomotion system is a combination of shafts, gears, and bearings. This required knowledge of what varied sizes of gears did, as well as pairing them with different mechanical components to get the appropriate paddling motion and torques necessary for movement. The major source for this knowledge came from the Machinery's Handbook, as well as Shigley's Mechanical Design Textbook. From here, we also had to learn how to press fit gears onto shafts and understand the different tolerances and material properties needed for success and durability. Shigley's Mechanical Design Textbook was also a vital source for understanding how to calculate stresses in certain gears.

CONCEPT EVALUATION

The requirements of this project required a complex design with three main subsystems. To create a successful prototype, our team had to brainstorm many different concepts for the locomotion system, body design, and electronic systems. The main subsystem of this project was the locomotion system, with the body design following and fitting around it. For the locomotion and body designs, a large concept generation was utilized to choose the best design. For electronics there was a large array of specific components that were needed, so concept evaluation was only necessary for motor and battery selection.

Locomotion Design Concepts

Our team came up with three different design concepts for the locomotion system. Each idea for the locomotion system needed to create a rotational to translational motion to be able to get a paddling motion as the output.

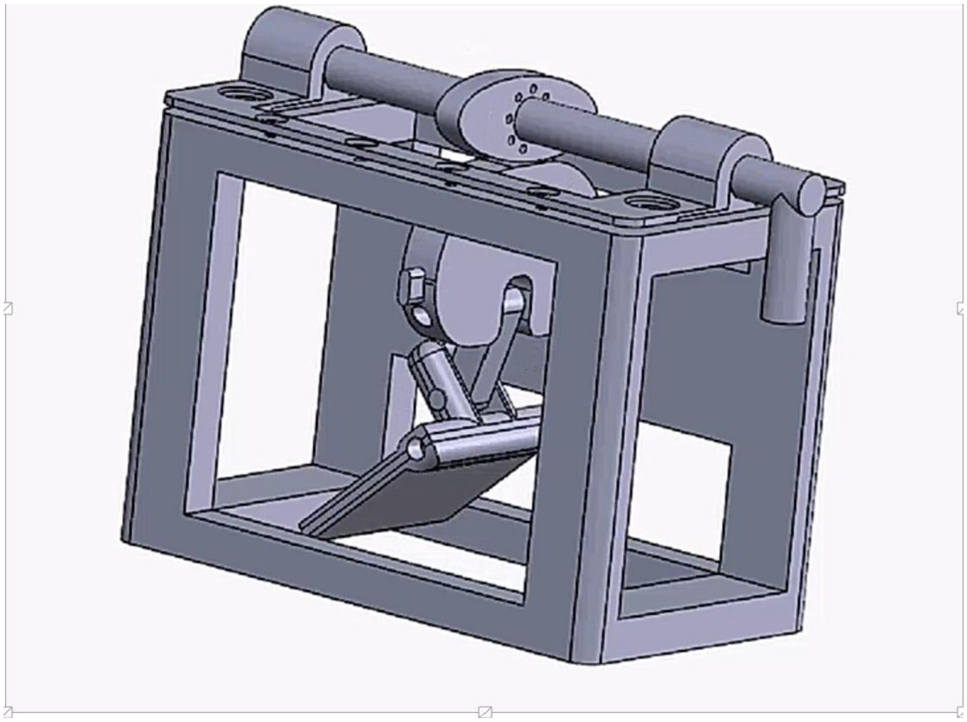


Figure 1. Camshaft locomotion design

The first idea for the locomotion was a camshaft model. This concept utilized a connecting rod similar to a 4-bar mechanism along with follower and connecting mechanisms and a simple drive shaft (cam) system. The drive shaft (cam) would create a rotational motion, and the connecting 4-bar mechanism would have a reciprocating translational motion that is passed through the follower and connector mechanisms and then outputs as a paddling motion. This design was very simple in number of parts and would be very low cost to manufacture, yet would have required custom manufactured pieces that would take a large amount of time to produce

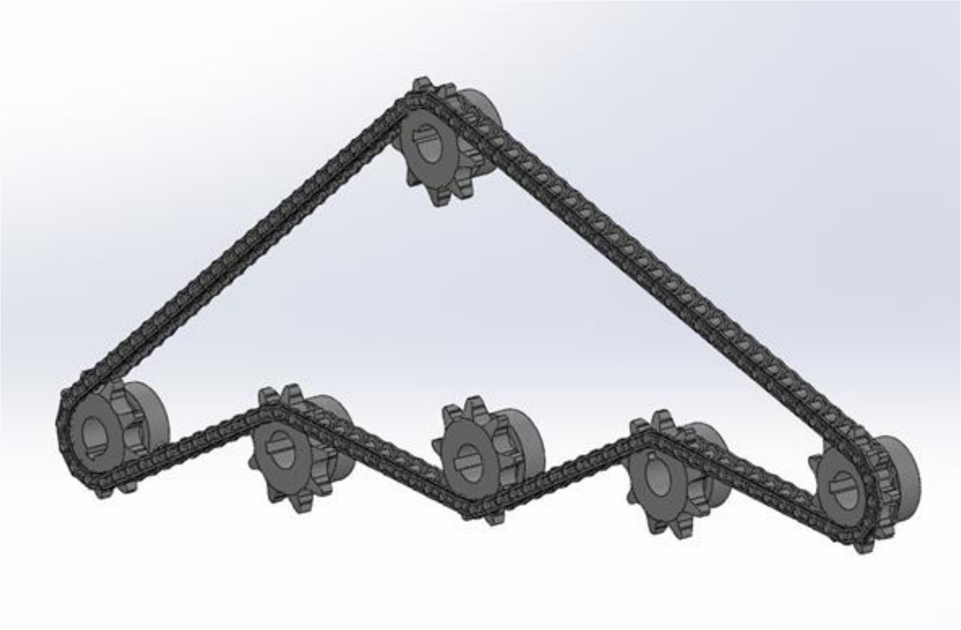


Figure 2. Bike chain locomotion system

The second concept was the chain and sprocket bike chain locomotion system. This design consisted of 6 steel sprockets and a single strand chain that drove the motion of the system. Mechanically speaking, this was a very simple design. It allows for high-speed motion in a relatively simple way without the need for rotational to translational transfer of motion. However, when it comes down to creating this, it is very large in size and not very adjustable. Bike chains are very difficult to create and appropriately fasten and tighten, and this would require a lot of additional testing that we didn’t have time for during the design and fabrication process.

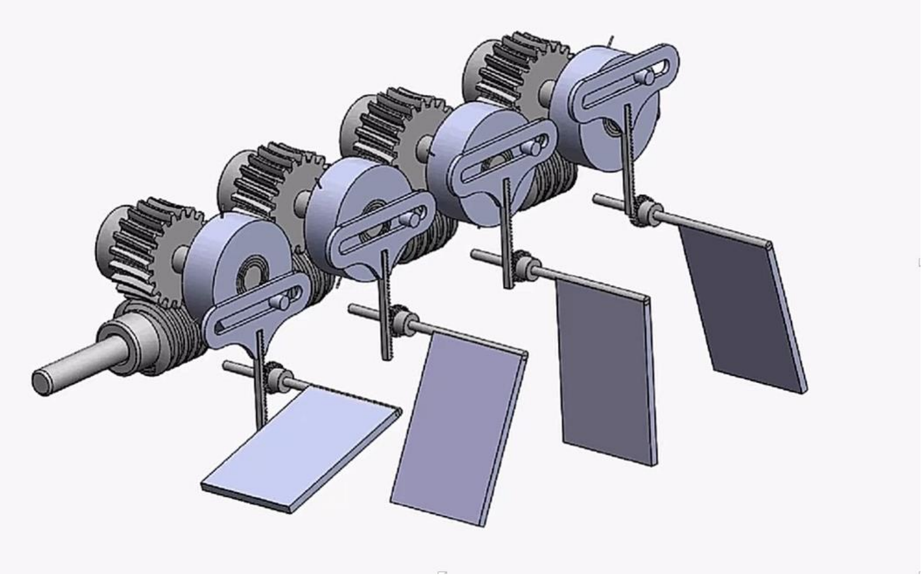
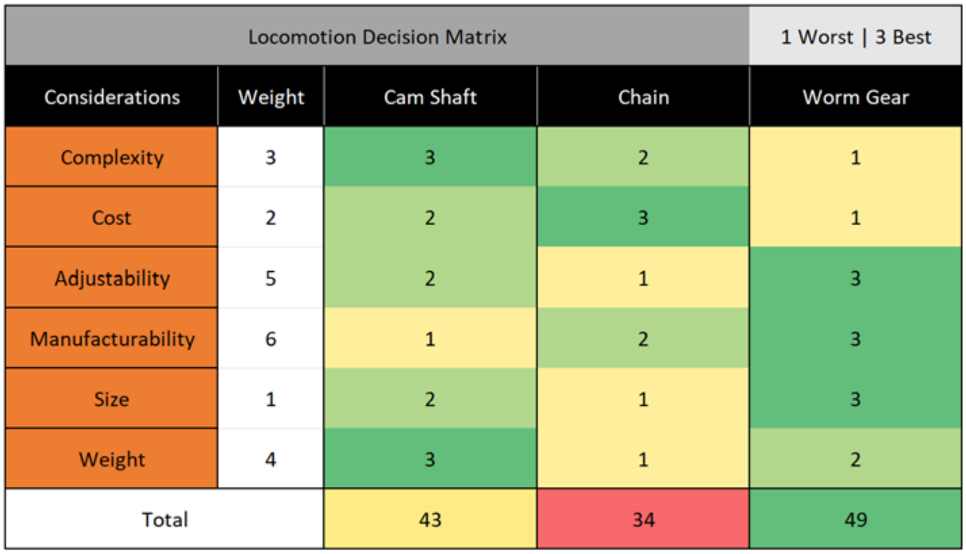


Figure 3. Worm and worm gear locomotion system

The last concept for the locomotion system, and ultimately the one we decided to choose, was the worm and worm gear system. This concept included three sub-assemblies, which were the main drive shaft, the rotational shaft, and the key mechanism, along with multiple gears to translate the motion. It utilizes a combination of worm drives, pin in slot, and rack and pinion gear mechanisms. This design, although it has quite a few parts, allows for smooth power delivery and greater control of speed and motion from the gearing. It also allowed for adjustability, and all parts could be purchased from McMaster-Carr. Therefore, it would be relatively easy to manufacture, even with the higher cost and number of parts and hardware.



Locomotion Decision Matrix				1 Worst | 3 Best
Considerations	Weight	Cam Shaft	Chain	Worm Gear
Complexity	3	3	2	1
Cost	2	2	3	1
Adjustability	5	2	1	3
Manufacturability	6	1	2	3
Size	1	2	1	3
Weight	4	3	1	2
Total		43	34	49

Figure 4. Locomotion Decision Matrix

After brainstorming each concept individually and putting together a decision matrix, we were able to select which design decision to choose for the locomotion system. In Figure , our teams' decision matrix is shown. Our considerations for the locomotion system included complexity, cost, adjustability, manufacturability, size, and weight. We wanted a design that was relatively simple to construct and manufacture, as well as cost-effective. Since this prototype would be for research purposes, we wanted to ensure that it could be adjustable as well. Lastly, we wanted to ensure that the size and weight of the locomotion system would not cause the overall design to become larger than the given 1-meter length nor cause the device to be too far below neutrally buoyant and just sink straight to the bottom in the water.

From the criteria in the decision matrix for locomotion, we assigned a score value to each system (1 being the worst and 3 being the best). We then weighed the criteria from 1 (least important) to 6 (most important), multiplied each score by the weight, then added each total criteria score for each concept to get an overall value for each subsystem. From this matrix, it was clear that the worm gear mechanism was the best fit for our design project. Even though it was rated lowest in cost and complexity due to the higher number of parts, its ease of manufacturing and adjustability made up for it and made it the best option to achieve the given requirements for this research prototype for metachronal paddling.

Body Design Concepts

After designing the locomotion system, we needed to create a body that was waterproof and able to fit around the locomotion design. To choose the best possible design, we brainstormed materials and manufacturing methods that could enable a successful body design. As a team, we came up with five ideas, but narrowed these down to the top three. We placed all five ideas in a decision matrix to ensure our choice selection was appropriate. The top three best and most accessible body design concepts were ABS plastic, acrylic, and aluminum.

	Weight	3D Printed ABS w/ Acetone Coating	Thermal Plastic Vacuum Former	Injection Molded Polycarbonate	Machined Aluminum	Acrylic
Cost	2	4	2	2	2	4
Complexity	4	4	3	2	2	3
Manufacturabilty	5	3	2	2	2	3
Strength	2	2	3	3	4	2
Waterproof	5	3	4	4	4	3
Weight	3	4	3	3	2	3
Total		70	61	57	56	63

Figure 5. Body Design Decision Matrix

Our top choice for body design was ABS plastic. ABS plastic was easily accessible and low cost due to OSU's 3D printing lab. It also would be low in complexity due to the machine taking a 3D model and printing the design itself, giving our team time for many other tasks. ABS plastic is light weight, easy to manufacture, and has many possible ways to waterproof. The main form of waterproofing would be to apply a coat of XTC-3D, which is a waterproofing applicator for 3D printed items. The only downside to using ABS plastic and 3D printing a body that is relatively large is that this printing process requires a lot of time for the machine to complete.

Figure 6. XTC-3D waterproof coating

Our second choice of material was acrylic. This material was also free and easily accessible through OSU's NCL lab. Acrylic is durable, easily manufacturable with laser cutting, and has multiple ways to waterproof it. The complexity of creating an acrylic body goes up due to having to create a model of the body that can be put together like a puzzle. Since acrylic is a stiff material that cannot be bent, all pieces and sides of the body need to be laser cut separately, then attached. This also adds to the difficulty in ensuring waterproof capabilities. However, there are many techniques for this, including acrylic welding, epoxy, and silicone sealant. Even though acrylic isn't the strongest material, it is a very viable, manufacturable, and appropriate choice for this research prototype.

Figure 7. Acrylic Weld

Even though aluminum was the lowest score in the body decision matrix, it was more feasible and accessible than thermal plastic vacuum forming or injection molded polycarbonate. So, we included it in our concept analysis. Aluminum is a very strong, light weight material and has the capability to be relatively easily waterproofed with welding techniques. However, it would be expensive, complex, and difficult to manufacture. We also performed preliminary stress and cost analysis to determine whether this option was more viable than the decision matrix was showing. The figure below shows a basic Solidworks model of a body constructed of 1/8'' aluminum sheets under a pressure equivalent to 10 feet of depth underwater.

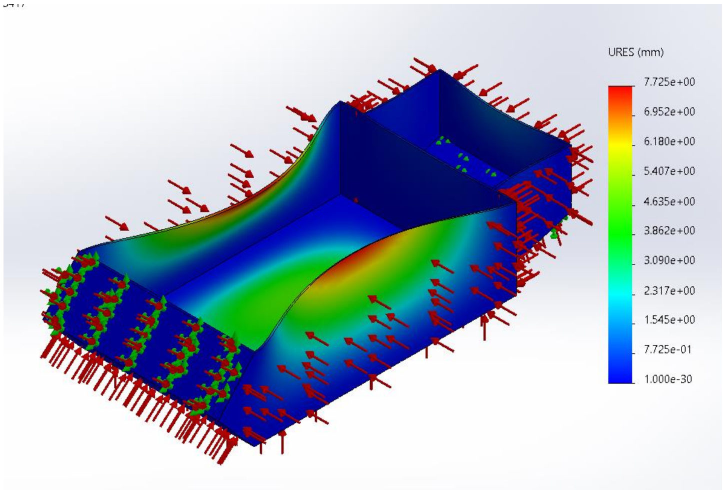


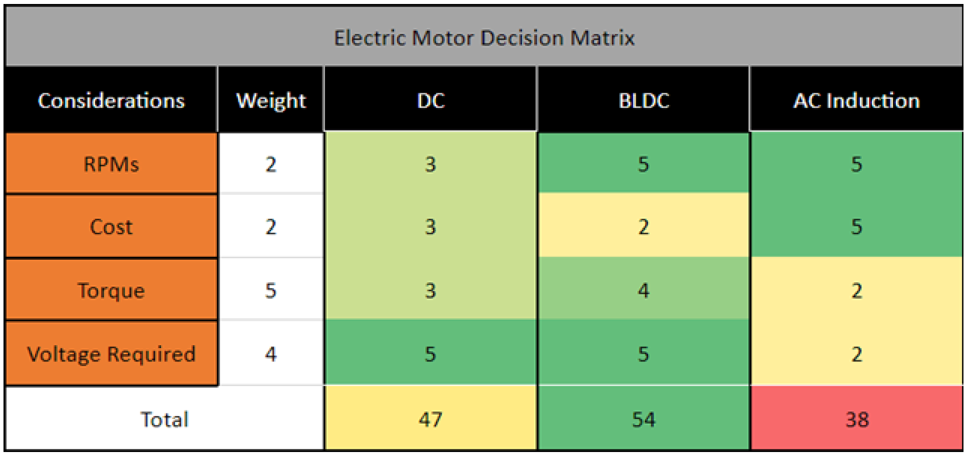
Figure 8. Aluminum Body FEA

As seen in Figure , the deflection of the walls would be ~7.5mm, which is well beyond acceptable tolerance. As such, this body design would likely require more than 1/8'' thick aluminum plates. Since two 24'' by 24'' by 1/8'' plates would already cost over $200 in raw materials, it was determined that this method of construction would be too expensive with our limited budget.

After analyzing the various possible materials and manufacturing methods for the body design, we ended up deciding to use ABS plastic and 3D print the body due to its low cost, low complexity, low weight, and numerous waterproofing techniques.

Motor Design Concepts

A system with such high torque and power outputs requires a very specific motor with high RPMs and high torque capabilities. The motor is what drives the locomotion system, so thorough power and torque analysis guided our team's decision on selecting a motor. The considerations that were considered here included RPMs, cost, torque, and required voltage. A scored scale of 1 to 5 representing worst to best was used.



Electric Motor Decision Matrix				
Considerations	**Weight**	**DC**	**BLDC**	**AC Induction**
RPMs	2	3	5	5
Cost	2	3	2	5
Torque	5	3	4	2
Voltage Required	4	5	5	2
Total		47	54	38

Figure 9. Motor Decision Matrix

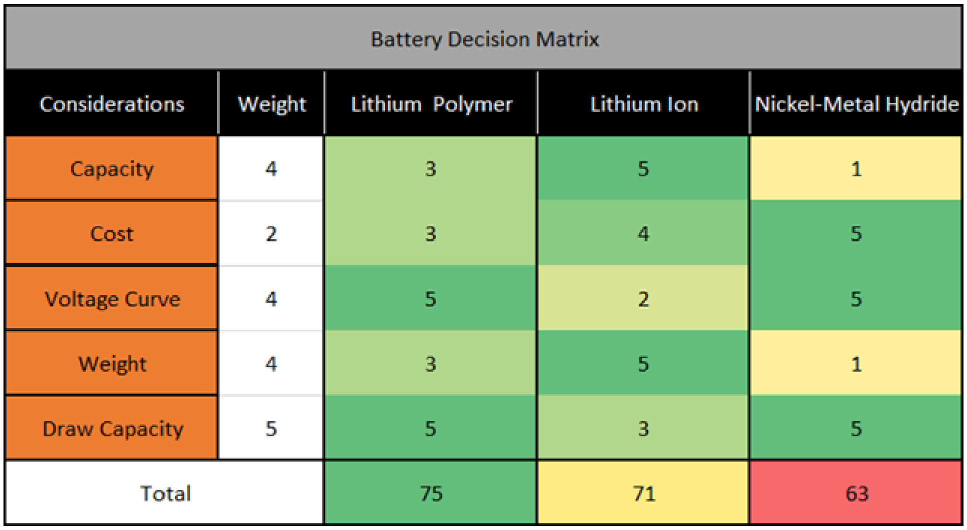
The first type of motor considered was a DC motor. A direct current motor is a type of electrical motor that converts direct electrical energy into mechanical energy by taking electric power and turning it into mechanical rotation. These motors are relatively low-cost, come in a wide array of sizes and power ratings, and have a reasonable torque tolerance and RPM output. However, they require a high amount of voltage to run.

The second type of motor that was considered was an AC motor. An alternating current motor is an electric motor that uses alternating current to convert electric energy into mechanical energy. They can output high torques with a lower voltage value. On the downside, they are usually high in cost and have low RPM outputs. Due to these constraints, this motor type was least plausible for our system.

The third and final type of motor was a BLDC motor. A brushless, direct current motor is an electric motor that is specifically designed for high performance. They have a high output of RPMs and torque, as well as a lower required voltage to run. The only downside to this motor is that they are higher in cost. Due to all the pros for this type of motor, we chose to go with BLDC motors to drive our locomotion system.

Battery Choice Concepts

The high torque and speed of this system requires a large amount of power input. To ensure an appropriate power source was onboard this device, an analysis of batteries was necessary to choose the best option. Our team took into consideration the capacity, cost, voltage curve, weight, and draw capacity of three types of batteries below to make our design selection. A value of 1 represents the lowest score and a 5 is the highest.



Battery Decision Matrix				
Considerations	Weight	Lithium Polymer	Lithium Ion	Nickel-Metal Hydride
Capacity	4	3	5	1
Cost	2	3	4	5
Voltage Curve	4	5	2	5
Weight	4	3	5	1
Draw Capacity	5	5	3	5
Total		75	71	63

Figure 10. Battery Decision Matrix

The first type of battery that we considered was Nickel-Metal Hydride batteries. These batteries are very low in cost, have a high voltage curve, and a high draw capacity. Due to the high voltage and draw capacities, they would be able to power the high amperages found in this system. However, they are very large, bulky, and the voltage decreases steadily and quickly as the pack is discharged. Due to this, they were the lowest scored on the decision matrix.

The second type of battery considered were Lithium-Ion batteries. These batteries have high energy densities, high capacity, and are very light weight. They can also last a long time when being discharged at a steady output rate. However, they have lower discharge rates and lower voltage curves and draw capacity, so they most likely will not be able to power our high-energy system for long. They also must be run at low current draws, which is another major reason these batteries were not chosen.

The final type of battery we considered, and the ones chosen for our system, were Lithium-Polymer batteries. These batteries are cost effective for the higher power they provide, can maintain a high nominal voltage as the pack is being used, and have a very high discharge capacity. The downside to these batteries is that they are a fire risk if overcharged or overdrawn, so they require voltage and circuit monitors when wired together. This is the battery that our team chose to use for our power supply due to its ability to keep the same output voltage and current for longer periods of time, as well as its lower price.

OVERALL SOLUTION, SUB SYSTEMS AND ANALYSIS

From the various concepts brainstormed and considered, our team chose the best options for each subsystem and put them into action. The figure below demonstrates the entire finalized design of the body with all parts and aspects added together in a single Solidworks model. All images of the final product can be viewed in Appendix A of this report. All CAD drawings can be found in Appendix B of this report.

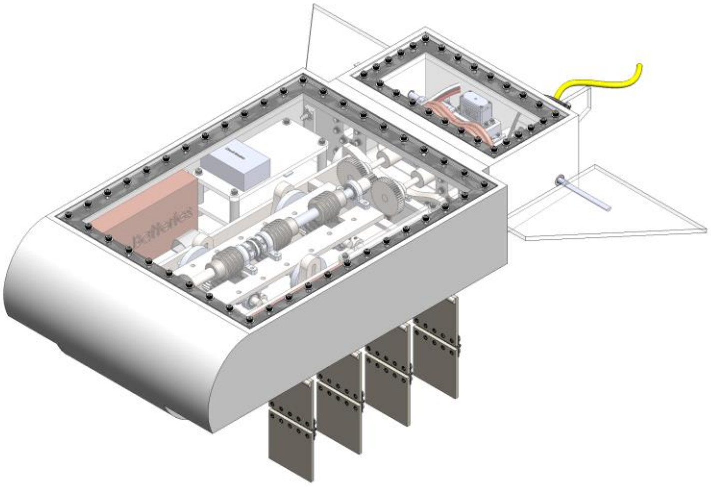


Figure 11. Full system Solidworks model

The full, overall design started with multiple smaller aspects that came together to create an overall, bio-inspired underwater vehicle. This project required a new locomotion design, as well as an electrical system with multiple components, sensors, wiring and coding logic, a waterproof body design, and a functioning paddle design. After concept generation and subsystem design selection, each individual assembly required strength and stress analysis for material and component selection, heat production analysis, torque calculations, and flow analysis.

Locomotion System

The locomotion system begins with two Neo Brushless Motors turning two gears that together drive a much smaller gear. This smaller gear is connected to a central keyed axis with four worms attached. These worms turn worm gears which are attached to one-way bearings. These one-way bearings are then attached to a key mechanism which turns a paddle shaft in an oscillatory back-and-forth motion. This movement allows a constant paddling motion to be controlled by a constant rotational motion. Below in Figure and Figure is a picture of the mechanisms and system.

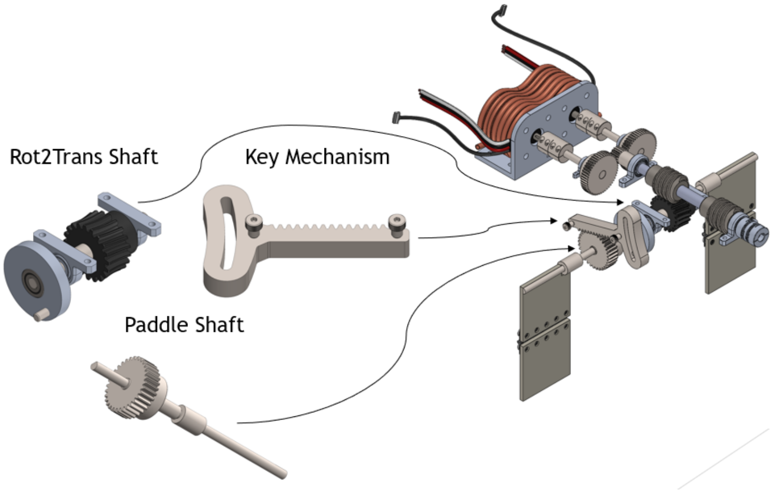


Figure 12. Full locomotion system

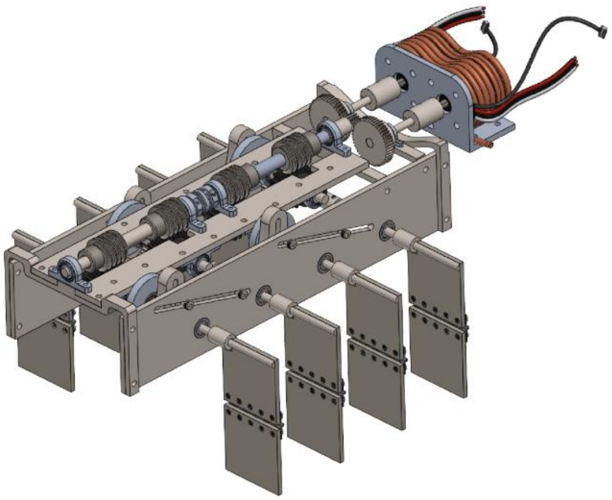


Figure 13. Fully modeled image of the locomotion system

Torque Calculations

The locomotion system design was the largest component that needed design and analysis. Due to this model being a large body consisting of multiple shafts, gears, bearings, and fastening devices, a lot of focus has been on whether the two motors can complete the necessary motion. To ensure that the design could withstand the motion needed to allow the device to move, in depth torque and stress calculations were performed on all the shafts, gears, and paddles. A free body diagram in Figure shows all forces that are acting on the locomotion system.

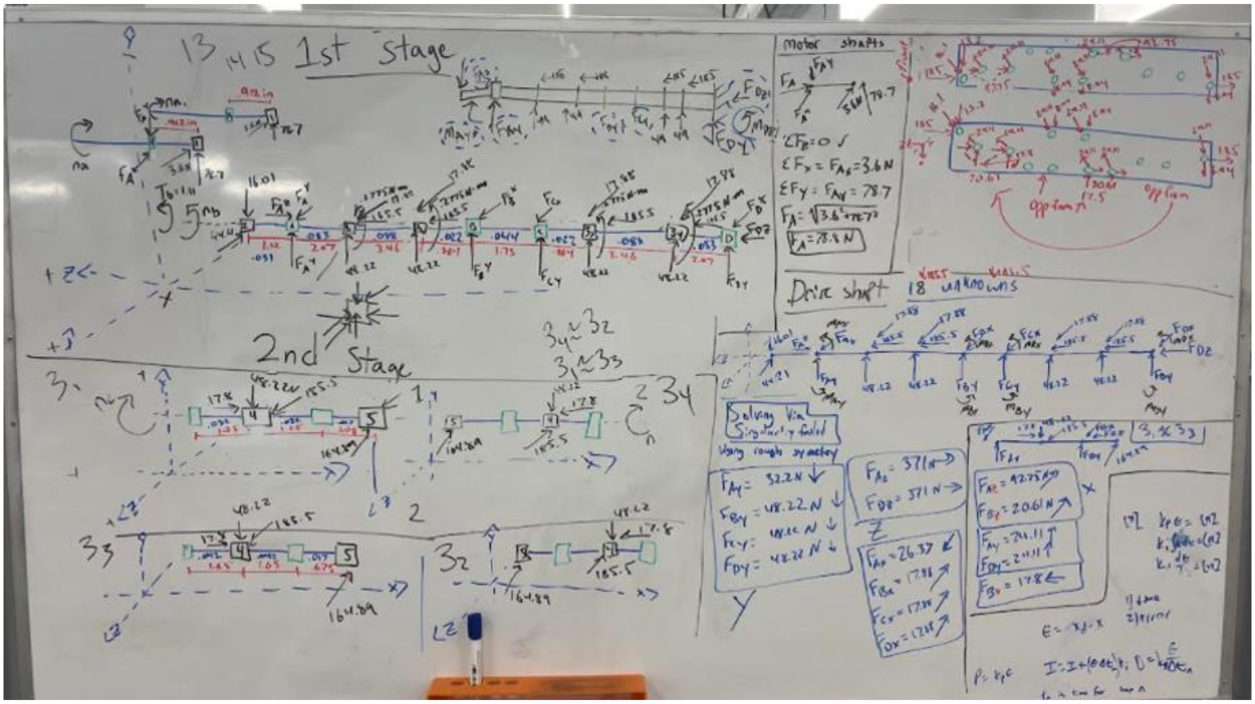


Figure 14. Free body diagram of all forces acting on the locomotion system

Motor – $RPM = 1800$

Motor Gear – $Pitch\ Diameter\ (pd_{mg}) = 0.050\ m, Teeth\ (N_{mg}) = 50, Pressure\ Angle\ (\phi_{mg}) = 20°$

Shaft Gear – $Pitch\ Diameter\ (pd_{sg}) = 0.015\ m, Teeth\ (N_{sg}) = 15, Pressure\ Angle\ (\phi_{sg}) = 20°$

Worm – $Pitch\ Diameter\ (pd_w) = 0.031\ m, Lead\ Angle\ (\lambda_w) = 3.73°, Pressure\ Angle\ (\phi_w) = 14.5°, Diameter\ (d_w) = 0.02997$ m

Worm Gear – $Pitch\ Diameter\ \left(pd_{wg}\right) = 0.040\ m, Teeth\ \left(N_{wg}\right) = 20, Pressure\ Angle\ \left(\phi_{wg}\right) = 14.5°, Diameter\ \left(d_{wg}\right) = 1.5748\ in$

Center Hub – $Pitch\ Diameter\ (pd_{ch}) = 0.0225\ m$

Key – $Pitch\ Diameter\ (pd_k) = 0.0185\ m, Pressure\ Angle\ (\phi_k) = 20°$

Paddle Gear – $Pitch\ Diameter\ (pd_{pg}) = 0.048\ m, Pressure\ Angle\ (\phi_{pg}) = 20°$

Motor Applied Torque

$$T_{motor} = 2.6 - 0.00041667(RPM) = 2.6 - 0.00041667(1800) = 1.85\ Nm\ (15.6\ lbs)$$

$$\omega_{motor} = \frac{2\pi}{60}(RPM) = \frac{2\pi}{60}(1800) = 188.5\ rad/s$$

$$P_{motor} = T_{motor} \times \omega_{motor} = 1.85 \times 188.5 = 348.725\ N = .349\ kN$$

Motor Gear Shaft Mesh

$$n_b = RPM\left(\frac{N_{mg}}{N_{sg}}\right) = 1800\left(\frac{50}{15}\right) = 6000\ RPM$$

$$\omega_b = n_b\left(\frac{2\pi}{60}\right) = 6000\left(\frac{2\pi}{60}\right) = 628.31\ rad/s$$

$$W_{12}^t = \frac{60000(P_{motor})}{\pi(pd_{mg})(RPM)} = \frac{60000(.349)}{\pi(0.05)(1800)} = 0.074\ kN = 74\ N$$

$$W_{12}^r = W_{12}^t \tan\phi_{mg} = 74\tan(20°) = 26.93\ N$$

Shaft Gear

$$\circlearrowright T_b = W_{12}^t\left(\frac{pd_{sg}}{2}\right) + W_{12}^t\left(\frac{pd_{sg}}{2}\right) = 2W_{12}^t\left(\frac{pd_{sg}}{2}\right) = 2(74)\left(\frac{0.015}{2}\right) = 1.11\ Nm$$

Drive Shaft

$$T_b = 1.11\ Nm$$

$$\omega_b = 628.31\ rad/s$$

$$P_{ds}^W = T_b \times \omega_b = (1.11)(628.31) = 697.4\ W = .6974\ kW$$

$$P_{ds}^{hp} = 1.341\left(P_{ds}^W\right) = .935\ hp$$

$$P_{each}^{hp} = \frac{P_{ds}^{hp}}{4} = .234\ hp$$

Worm

$$V_3 = \frac{\pi(1.22)n_b}{12} = \frac{\pi(1.22)(6000)}{12} = 1916.4\ ft/min$$

$$W_3^t = \frac{33000(P_{each}^{hp})}{V_3} = \frac{33000(.234)}{1916.4} = -4.02\ lbf = -17.88\ N$$

$$f = 0.03$$

$$W_3 = \frac{W_3^t}{\cos\phi_w \sin\lambda_w + f\cos\lambda_w} = \frac{4.01}{\cos(14.5)\sin(3.73) + 0.03\cos(3.73)} = 43.32\ lbf$$

$$W_3^y = W_3 \sin\phi_w = 13.32\sin(14.5) = -10.84\ lbf$$

$$W_3^z = W_3(\cos\phi_w \cos\lambda_w - f\sin\lambda_w) = 43.22(\cos(14.5)\cos(3.73) - 0.03\sin(3.73) = -41.7\ lbf$$

Worm Gear

$$W_{43}^z = -W_3^z = 41.7\ lbf$$

$$W_{43}^y = -W_3^y = 10.84\ lbf$$

$$W_{43}^t = -W_3^t = 4.02\ lbf$$

$$\circlearrowright T_c = W_{43}^z \times \left(\frac{d_{wg}}{2}\right) = (41.7)\left(\frac{1.5748}{2}\right) = 32.83 lbin = 3.71\ Nm$$

Outer Hub

$$F_{pin} = \frac{T_c}{pd_{ch}} = \frac{3.71}{0.0225} = 164.89\ N$$

Key/Paddle Gear

$$W_{67}^t = F_{pin} = 164.89\ N$$

$$W_{67}^r = W_{67}^t \tan(\phi_{pg}) = 164.89\tan(20) = -60\ N$$

$$F_{d7}^x = -164.89\ N$$

$$F_{d7}^y = -W_{67}^r = 60\ N$$

Output Torque

$$T_{paddle} = W_{67}^t\left(\frac{pd_{pg}}{2}\right) = 164.89\left(\frac{0.048}{2}\right) = 3.96\ Nm$$

$$T_{paddle_{max}}^{each} = \left(\frac{T_{paddle}}{2}\right) = \left(\frac{3.96}{2}\right) = \mathbf{1.98\ Nm}$$

Based on the output torque calculation above, each of the eight paddles would be needed to exert a torque of 1.98 Nm. The motors we have selected can do this and have extra room in case the torque needed is higher in an emergency. Below shows a graphical representation of the torque necessary vs paddle length.

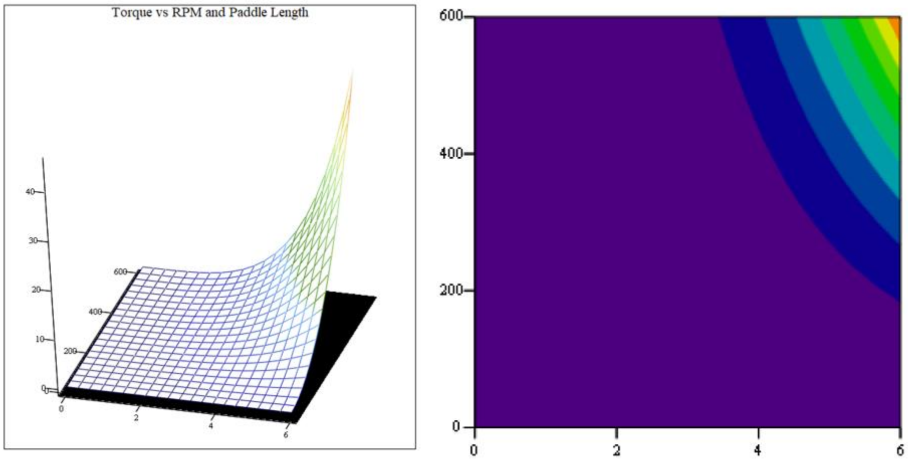


Figure 15. Torque graphs of the motors

Motor Selection

Because of the high torques necessary to turn the locomotion system, robust motors had to be identified and used. The Neo Brushless Motors were found to have high enough torques (coming in around 2.5 Nm of empirical torque) without suffering a reduction in RPMs. Along with these specifications, the motors came with ESCs which reduced the work necessary to get the motors working. Due to the motor controller, our group would be able to control the motors very easily. The chart in Figure shows the RPM and torque chart provided for the motors by RevRobotics. Our group deduced that 1800 RPM would be necessary with our gear reductions to reach the desirable 6000 RPM needed for 10 Hz to be reached underwater.

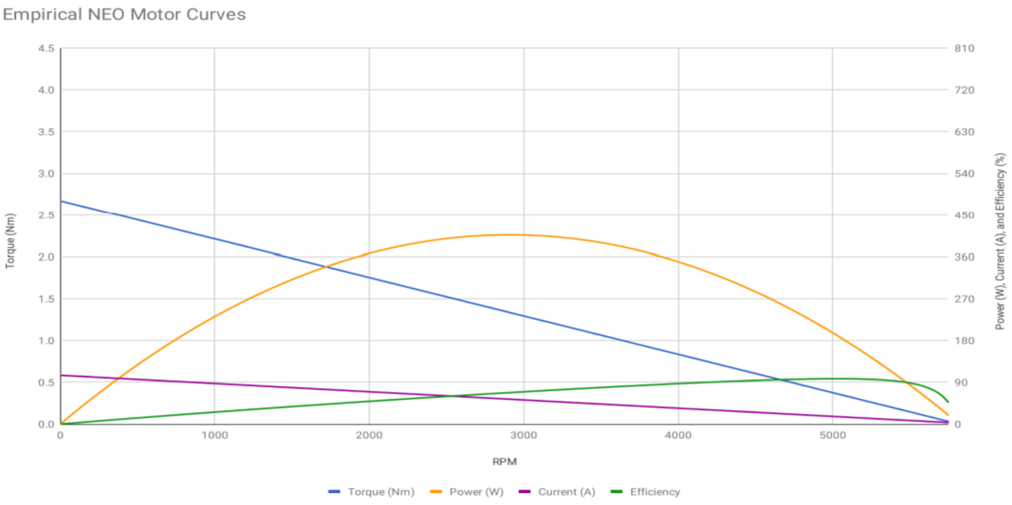


Figure 16. RevRobotics chart comparing torque, power, current, and efficiency

Body Design

Based upon the scope of the project, the design of the body would have to fulfill several different requirements to ensure the best performance of the device is achieved. The first major aspect of the body design was material selection. We originally chose for the body to be comprised of ABS plastic that was to be 3D-Printed into the body shape that fits around the locomotion system. The decision to use the 3D print ABS plastic was made by considering the cheaper price in comparison to some other materials and the ability to print more customizable and robust components of the design. Our analysis matrix is shown earlier. As shown in Figure , the model consisted of two different compartments. The first one being the main compartment, where the locomotion system and electronic components such as the pump, PCA, and batteries were stored. The second being the rear compartment, which housed the servos and motors, as well as a cooling system and other control aspects of the device. Overall, with the print of the body we are looking at dimensions of 28” x 14” x 8” which fell well within the 1 meter (39.37 in.) body length limit given by the project mentor, Dr. Santhanakrishnan.

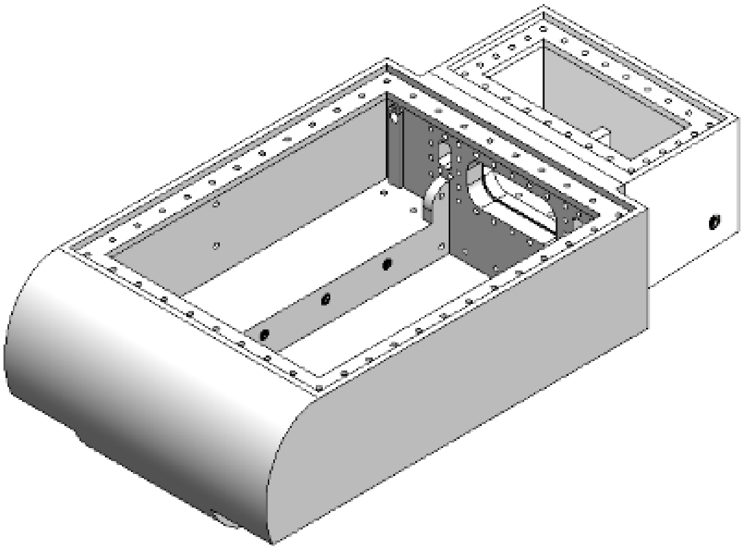


Figure 17. Full body model for ABS plastic

Additionally, to ensure that the material could withstand the pressures at the expected depth of 10 feet, we ran a Solidworks stress simulation to estimate the maximum deflection possible. In the figure below, the maximum deflection is shown and expected to be approximately 2 mm, well within an allowable tolerance for deflection in an underwater vehicle.

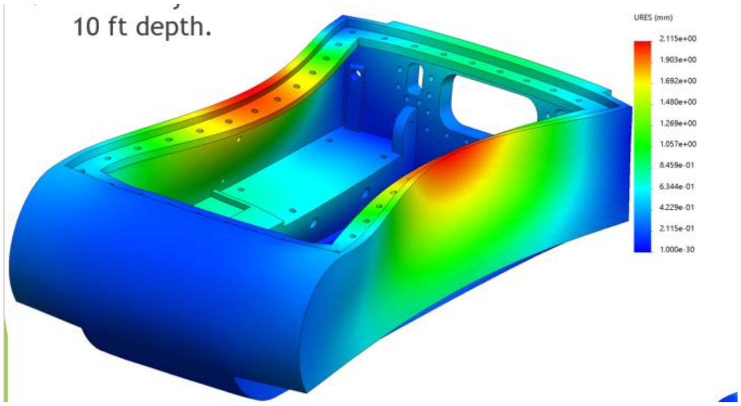


Figure 18. FEA showing deflection of acrylic at 10 feet

The use of ABS plastic as the body material was the original plan due to its desirable characteristics and ease of manufacturing, as seen earlier in the concept comparative matrix. When issues arose with the 3D printers and multiple failed prints, we had to switch to our alternative body design, which was acrylic. To create an acrylic body, the team created a jigsaw 3D model of pieces to be laser cut (seen in Figure) and connected. The acrylic body was designed with a thickness of approximately 0.375 inches, which gave us very close deflections to ABS plastic (if not less so) at maximum depth. From the laser cut pieces, we then had to acrylic weld each piece together, along with epoxy and silicone to seal all gaps and corners to ensure that the body was securely fastened together, as well as fully waterproof. Figure shows our body design fully assembled (without the lid).

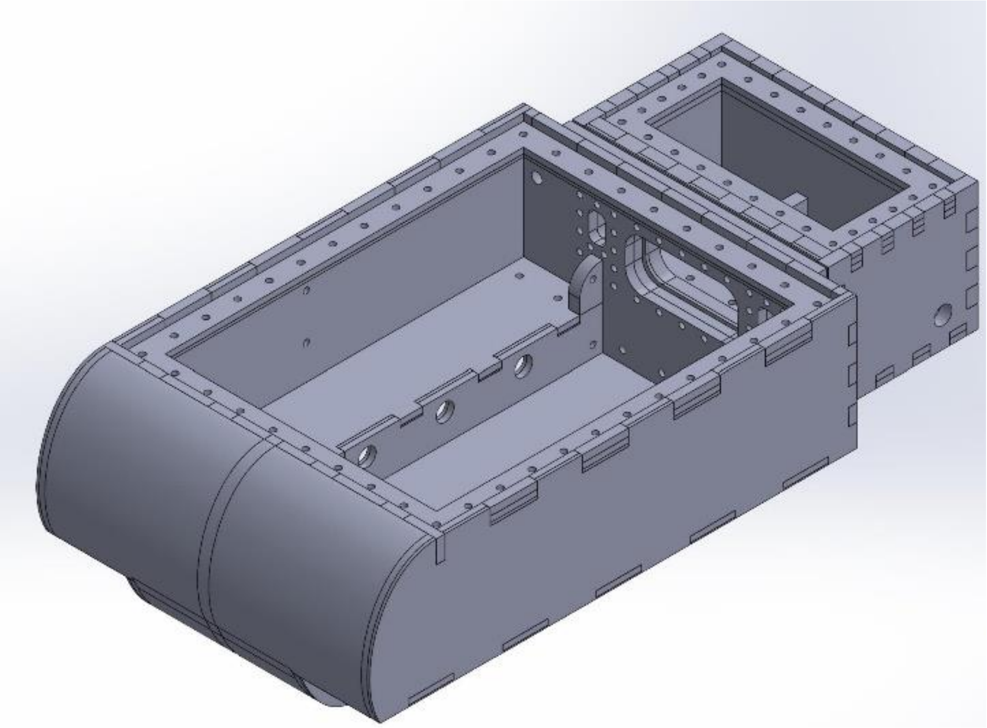


Figure 19. Jigsaw body model for acrylic laser cutting

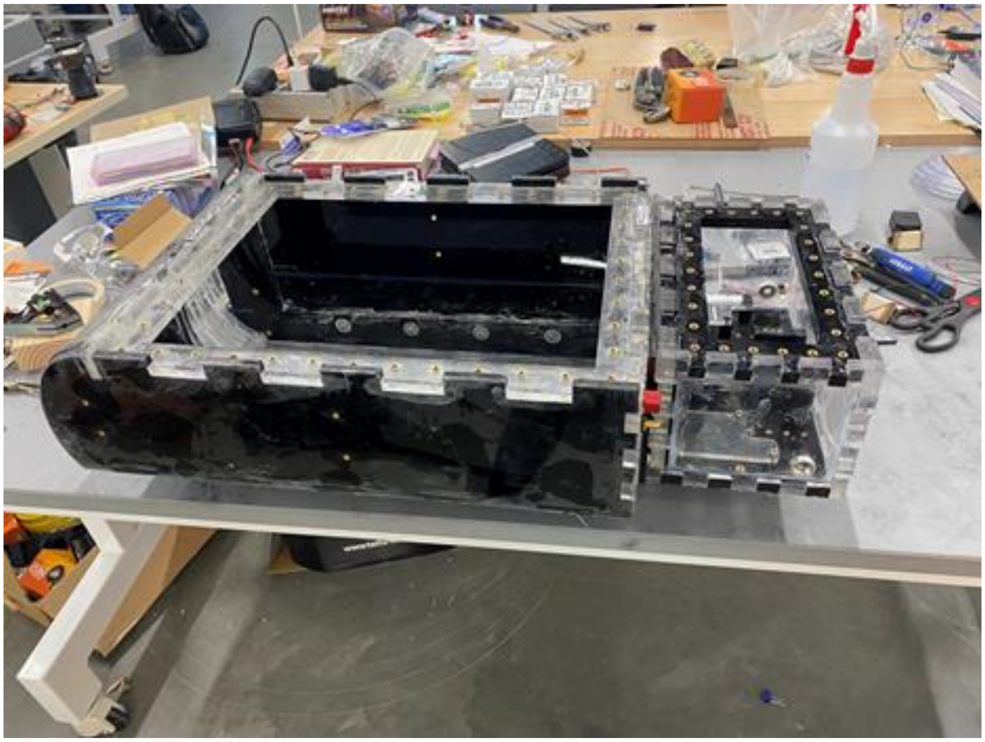


Figure 20. Acrylic body assembled

Upon the application of acrylic weld, epoxy, and silicone waterproof testing would immediately start taking place. It was during this stage that it was realized that a rubberized coating would also need to be externally applied to help cover over any imperfections that may have present after the initial waterproofing applications. To go along with these waterproofing methods, we also utilized a series of gaskets to help keep water from breaching the body. The gaskets were made by laser cutting sheets of neoprene rubber to desired size in attempt to provide proper suction to the waterproof seal. The gaskets were used in three different locations on the body, the first being the main lid which served to keep the main compartment watertight. The second gasket served a similar purpose as the first gasket but for the rear compartment of the body. The third gasket was the most unique as it served to create a seal between the main and rear compartments of the body. Provided in Figure is the cross-section diagram of how the gaskets were implemented into the body with all its components, including the heat set threaded inserts, acrylic lid, washer, and bolts.

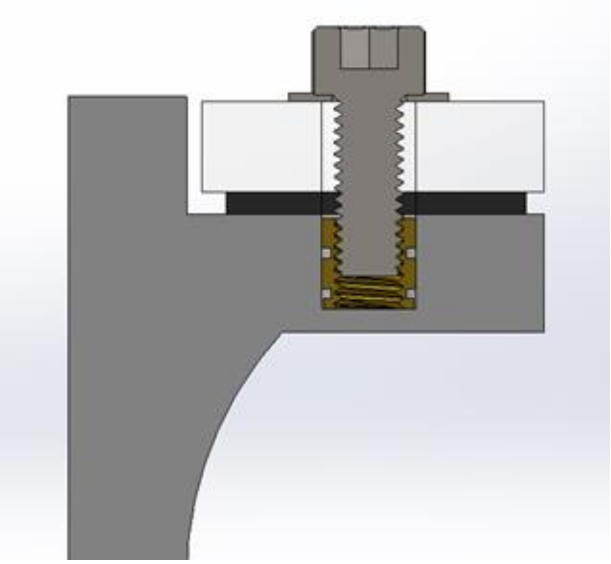


Figure 21. Waterproof gasket placement

The next major component of the body design was weight and buoyancy. Since this design is to be an underwater vehicle, we needed to have the prototype remain submerged and at its desired depth location in the water while running. So, buoyancy calculations were performed to find the required weight to keep the device underwater at a depth of 10 feet. This desired weight is known as neutral buoyancy. For these buoyancy calculations, we were first able to calculate the total volume displaced by using the Solidworks model of our body design. After analyzing it we found that the volume displaced was 0.039m^3. Taking this volume, we then were able calculate the buoyancy force needed by using the following formula:

$$Force_{Buoy} = \rho v g = 997\frac{kg}{m^3} * 0.0390m^3 * 9.81\frac{m}{s^2} = 381.442N = 85.75lbs$$

With the scope of our mission being to create an underwater device, we needed a body that was slightly negatively buoyant to avoid our vehicle from rising to the surface while it is operating since metachronal paddling creates a slight upward thrust. To achieve this goal, it was found that the mass of approximately 39 kg (85.98 lbs) was needed to achieve the desired weight for appropriate buoyancy. To reach this necessary weight, the addition of internal weight plates had to be included. Pictured below in Figure and Figure is the main body compartment along with its 1” thick stainless-steel plates. We chose steel plates due to their heavy weight and lower cost, as well as ease of accessibility and machinability. These metal weight plates are to be placed underneath the electronics platforms on either side of the locomotion system. They can be easily accessed here and taken out to be milled or cut down to adjust the weight of the body.

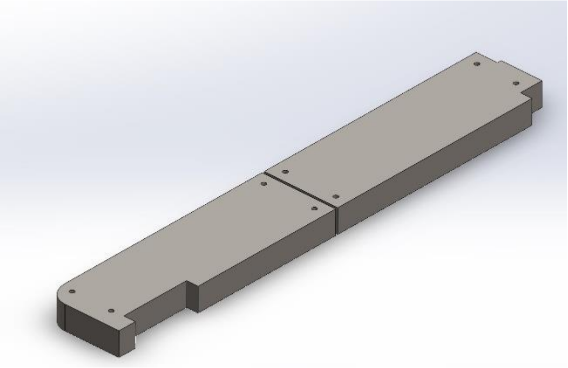


Figure 22. Internal Weight Plate Design

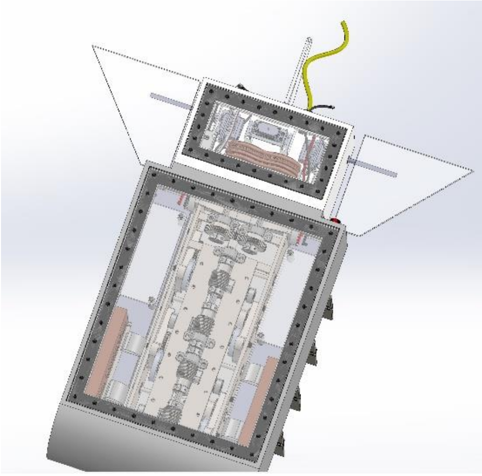


Figure 23. Plates to be located under white electronic platforms in body

Buoyancy

Center of Buoyancy

Another important aspect of an underwater vehicle's stability underwater is the center of buoyancy and center of mass. The center of buoyancy can be calculated by finding the geometric centroid of an object and comparing its position to the position of the center of gravity. Both the center of buoyancy and gravity were found utilizing Solidworks and its material property and design tables for our model. The center of mass was found using a built-in Solidworks function. The results can be found in Figure .

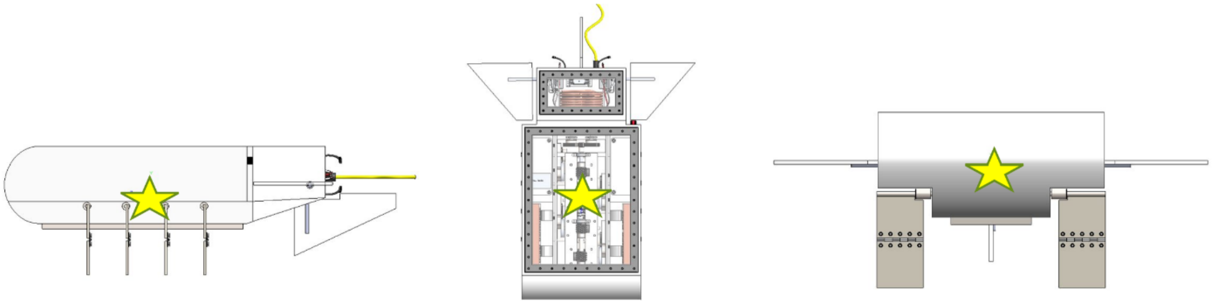


Figure 24. Center of mass location

Solidworks does not include a built-in center of buoyancy feature. This, however, can be found by creating a model of equivalent external geometry designed with a constant density throughout. The center of mass of this object will also reflect the center of gravity. From there, you can find the centroid of the shape and locate the center of buoyancy in comparison to center of mass. By comparing the coordinate of the center of buoyancy to the center of mass, the resting angle of the design can be found. This angle is shown in Figure and displays that the model will have a slight downward pitch angle under maximum system forces. This pitch downward, in theory, will help with stabilizing the device from the upward thrust from the metachronal paddling.

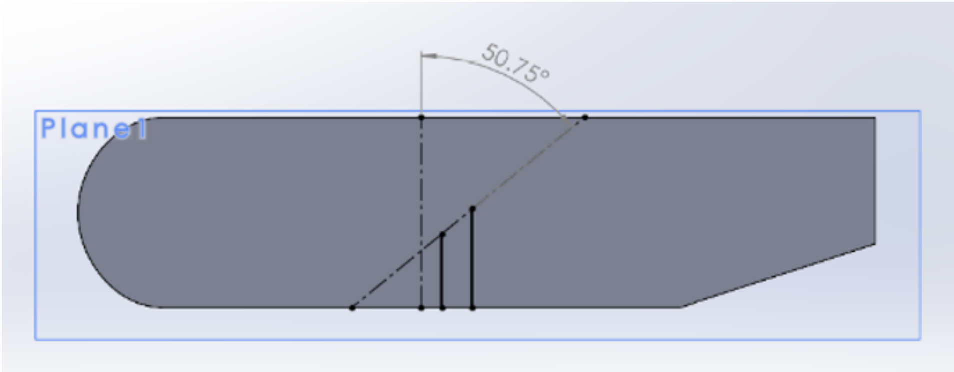


Figure 25. Center of buoyancy and resting angle for the submerged body

Center of Pressure

The center of pressure was also found by using Solidworks flow simulation, as shown in Figure below. This flow simulation takes the body and applies the force of fluid on the system to determine how the device will naturally tilt in real life.

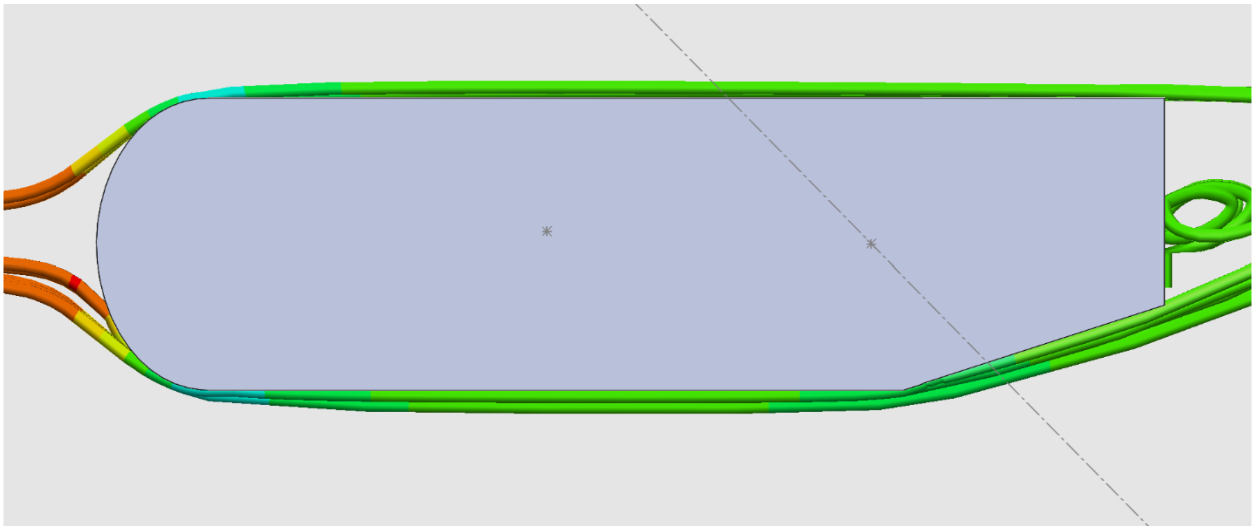


Figure 26. Flow simulation for center of pressure

Pressure Stress of Shaft Collar

In order to adequately fasten the collars of the locomotion system to the shafts, press fitting was the best option. Press fitting allowed for tight, secure fastening that would hold and last under the high torque and stress in the system. The two materials compared here are 2024 Aluminum and 304 Stainless Steel, as can be seen in Figure . The shaft is made of 304 Stainless Steel and the collar is made of 2024 Aluminum.

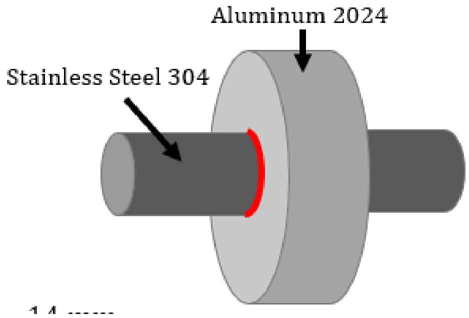


Figure 27. Press fit diagram of an aluminum collar onto a stainless-steel shaft

Calculations on various materials were performed to find the best fit for both shaft and collar material that could withstand the forces in both the locomotion system and the press fitting. From each materials modulus of elasticity, Poisson ratio, shaft diameters, collar arc length, and static friction coefficients, the displacements of each material option were found and then compared to the maximum force and pressure in the system. These calculations, shown below, led the team to decide on a 2024 Aluminum collar and a 304 Stainless Steel shaft.

2024 Aluminum: $\nu_{Al-2024} = 0.33, E_{Al-2024} = 73.1\ GPa$

$$\nu_{SS-304} = 00.265, E_{SS-304} = 190\ GPa$$

$\mu_{Al-SS} = 0.4$

$$arclength = 36.3226\, mm$$

$$r = \frac{Arcl}{2\pi} = \frac{36.3226}{2\pi} = 5.7809\, mm$$

$$D_{new} = 2r = 2(5.7809) = 11.562\, mm$$

$$\delta_{max} = D_{original} - D_{new} = 12mm - 11.562\, mm = 0.438 \text{ mm}$$

$$A = 2\pi rl = 2\pi(5.7809\, mm)(11\, mm)$$

$$F = \mu AP_{max} = (0.4)(399.547\,)(P_{max}) = 370$$

P_{max} = 2.315

$$\delta = P_{max}R\left[\frac{1}{E_{Al}}\left(\frac{r_o^2 + R^2}{r_o^2 - R^2} + \nu_{Al}\right) + \frac{1}{E_{SS}}\left(\frac{R^2 + r_i^2}{R^2 - r_i^2} - \nu_{SS}\right)\right]$$

$$\delta = (2.315)(6)\left[\frac{1}{73.1E9}\left(\frac{14^2 + 6^2}{14^2 - 6^2} + 0.33\right) + \frac{1}{190E9}\left(\frac{6^2 + 0}{6^2 - 0} - 0.265\right)\right]$$

$$\delta = 3.923E - 10\, mm$$

$$\boldsymbol{\delta_{max} > \delta}$$

$$\mathbf{0.438 > 3.923E - 10}$$

As we can see, there is no risk of axial movement as the delta $\delta_{max}$is much larger than the calculated delta max for the 2024 Aluminum collar.

Tether

Since this design operates within an underwater environment, it is important that the communication tether not interfere with the motion of the ROV. The Fathom ROV Tether from BlueRobotics was chosen for this purpose as it offered a combination of low cost, neutral buoyancy, and redundant wires.

Figure 28. Fathom ROV Tether

Tether Bulkhead Fitting

To ensure that the tether would maintain a watertight seal, a bulkhead fitting was attached to the body through the rear compartment. For this purpose, the 7.5mm WetLink Penetrator bulkhead fitting from BlueRobotics was chosen as it was designed to fit the Fathom ROV Tether specifically.

Figure 29. 7.5mm WetLink Penetrator Bulkhead fitting

Heat Calculations

Due to the motors having high torque and RPM, a large amount of heat from each sub system is produced when operational. To mitigate this risk, a cooling system was implemented into the design. A small self-priming pump was inserted that would pull water from the outside, push it through copper coils surrounding the engines, and then release the heated water back into the environment (Figure and Figure). The copper coils would be secured to the motors via their shape and positioning. The entrance and exit tubing, as well as tubing from the pump, would be made of PEX tubing, with PEX adaptors attaching this to the copper tubing around the motor.

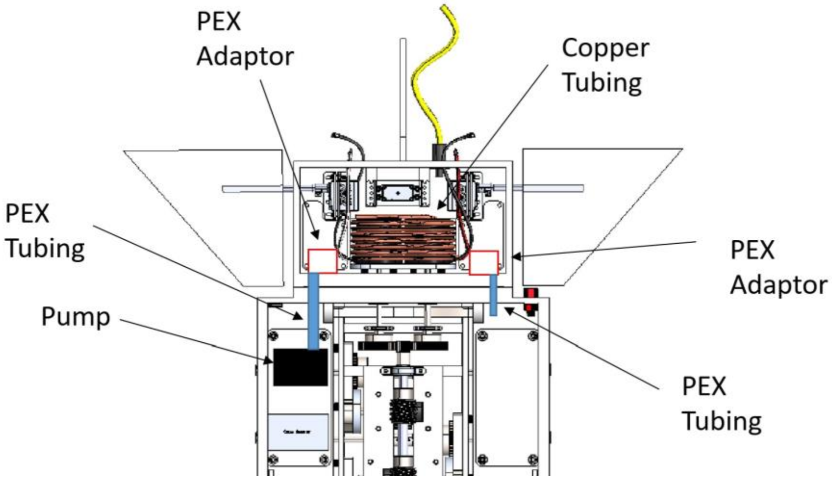


Figure 30. Design for the cooling system location

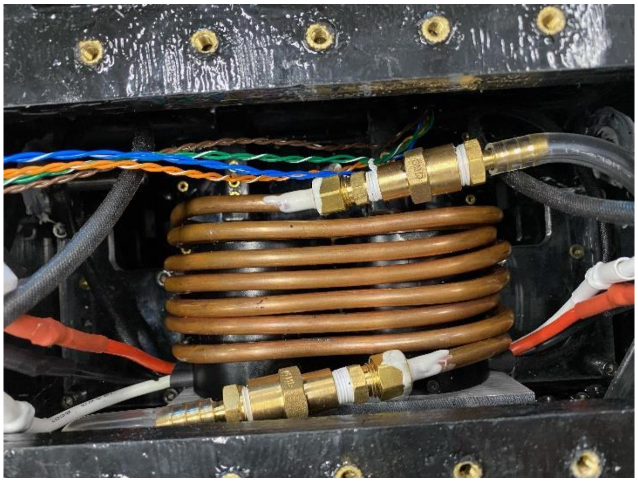


Figure 31. Copper coiling around motors in rear body compartment

Motor

Heat production calculations were performed to ensure the cooling system was necessary and to test the amount of heat that would be dissipated by it. The values for the motors were found using the RevRobotics Neo Brushless Motor datasheet that came with the motors. Due to the presence of two motors, we multiplied the singular motor value by two.

$$\dot{Q}_{motor} = \mathbf{227.87\ W}$$

$$2\dot{Q}_{motor} = \mathbf{455.74\ W}$$

Pump

$$Q_{pump} = LK(T_1 - T_2) = (2.55)(400)(298.15 - 328.15) = -30600$$

$$\dot{m} = \rho\omega(flow\ rate) \times 0.70 = (997)(0.0006)\left(\frac{1}{60}\right)(0.7) = 0.00997$$

$$\dot{Q}_{pump} = Q_{pump}\dot{m} = (-30600)(0.00997) = -\mathbf{213.56\ W}$$

Gears

Although lubrication of the gears is present, some heat is still produced in the locomotion system. This is because the worm gears rely on friction to function, which in turn generates heat. These calculations give even more reason as to why a cooling system is necessary in this submerged vehicle.

Worm – $Pressure\ angle(\phi_w) = 14.5°, length\ (l_w) = 46\ mm, Gear\ Pitch\ Diameter\ (d_{gpd}) = 1.22\ in, Outer\ Diameter\ (d_o) = 35\ mm, RPM = 6000, Lead\ Angle\ (\lambda_w) = 3.73°$

Worm Gear – $Gear\ Diameter\ (d_g) = 1.9685\ in, Teeth\ (N_g) = 20$

$$V_g = \frac{\pi(d_g)\frac{RPM}{N_g}}{12} = \frac{\pi(1.9685)(\frac{6000}{20})}{12} = 154.61\ ft/min$$

$$V_w = \frac{\pi(d_{gpd})RPM}{12} = \frac{\pi(1.22)(6000)}{12} = 1884.96\ ft/min$$

$$V_s = \frac{\pi d_{gpd} RPM}{12\cos(\lambda_w)} = \frac{\pi(1.22)(6000)}{12\cos(3.73)} = 1920.59\ ft/min$$

$$f = 0.103\exp(-0.110(V_s)^{0.450}) + 0.012 = 0.103\exp(-0.110(1920.59)^{0.450}) + 0.012 = 0.0158$$

$$e = \frac{\cos(\phi_w) - f\tan(\lambda_w)}{\cos(\phi_w) + f\cot(\lambda_w)} = \frac{\cos(14.5) - f\tan(3.73)}{\cos(14.5) + f\cot(3.73)} = 0.798$$

From Rev and Online – $n_d = 1, K_a = 1.44, H_o = 0.544$

$$W_{Gt} = \frac{33000 n_d K_a H_o}{V_g} = \frac{33000(1)(1.44)(0.544)}{154.61} = 209.52$$

$$W_{wt} = W_{Gt}\frac{\cos\phi_w \sin\lambda_w + f\cos\lambda_w}{\cos\phi_w \cos\lambda_w - f\sin\lambda_w} = (209.52)\frac{\cos(14.5)\sin(3.73) + f\cos(3.73)}{\cos(14.5)\cos(3.73) - f\sin(3.73)} = 16.99$$

$$H_w = \frac{W_{wt}V_w}{33000} = \frac{(16.99)(1884.96)}{33000} = 0.97\ hp$$

$$H_{loss} = 33000(1-e)H_w = 33000(1-0.798)(0.97) = 6466.02\ ft.lbf/min$$

$$H_{loss}^{W} = 0.023 \times H_{loss} = 0.023(6466.02) = \mathbf{146.13\ W}$$

Body Heat Loss

To measure the heat loss via convection and the water, we first assumed the inside of the vehicle to be 100°C and the water temperature to be 25°C. These values were based off temperature charts that came with the Neo Brushless Motor datasheet and an average temperature of water. The h1 and h2 values came from online charts regarding static air and water, respectively. The area of 0.613 m^2 was the surface area of the vehicle from the Solidworks model. The K value of 0.2 was the thermal conductivity coefficient of (the material of the walls). The infill value was necessary as the inner portion of the wall is indeed infill and therefore only 25% full. It was calculated by taking the full wall width, 0.375 inches, and subtracting the values of the inner and outer wall thickness, then multiplying the result by 0.25. The inner 'in' and 'out' wall thickness were, as stated before, the thickness of the walls.

$$\dot{Q}_{body} = \frac{T_{\infty_1} - T_{\infty_2}}{R_{total}} = \frac{100℃ - 25℃}{0.1538} = 487.67\ W$$

$$R_{total} = R_{conv}^{in} + R_{wall}^{in} + R_{wall}^{infill} + R_{wall}^{out} + R_{conv}^{out} = \frac{1}{h_1 A} + \frac{L}{kA} + \frac{L}{kA} + \frac{L}{kA} + \frac{1}{h_2 A}$$

$$= \frac{1}{(50)(0.613)} + \frac{1.6E-3}{(.175)(0.613)} + \frac{2.34E-3}{(.175)(0.613)} + \frac{1.6E-3}{(.175)(0.613)} + \frac{1}{(1140)(0.613)} = 0.1538$$

Total Heat Loss

Without Cooling System

$$\dot{Q}_{no.cool} = \dot{Q}_{motor} + \dot{Q}_{Gears} - \dot{Q}_{body} = 455.74\ W + 146.13\ W - 487.67\ W = \mathbf{114.2\ W}$$

With Cooling System

$$\dot{Q}_{cool} = \dot{Q}_{motor} + \dot{Q}_{Gears} - \dot{Q}_{body} - \dot{Q}_{pump} = 455.74\ W + 146.13\ W - 487.67\ W = \mathbf{-99.37\ W}$$

Without the heating system, there is a positive increase of heat within the body. However, with the addition of the pump, we will have the necessary heat dissipation to avoid internal damage.

Paddle Drag

Initial Paddle Drag Estimate

For the purposes of ensuring that our design can withstand the forces of a 10 Hz paddling rate, we initially calculated paddle drag as assuming the paddle as a rectangular cross section moving linearly through the water at the expected tangential velocity at a 10 Hz paddling rate. This would ensure that all aspects of our design would incorporate a natural factor of safety for higher-than-expected stress loads.

$$F_{drag} = \frac{1}{2}\rho CdAv^2$$

$$A = L \times w$$

$$v = L \times \omega$$

$$F_{drag} = \frac{1}{2}\rho Cdw\omega^2 L^3$$

- With $\rho = 997\ \frac{kg}{m^3}$, $C_d = 1.15$, $w = 3\ in$, $\omega =$ 62.83, and $L = 6\ in$:
  $F_{drag,linear} = 615\ N$

True Paddle Drag

Since the paddles translate radially and not rotationally, the actual expected drag will be much lower than linear translation would suggest. We created a second function to gather a more accurate expectation of the total drag on the paddle.

$$F_{drag} = \frac{1}{2}\rho CdAv^2$$

$$F_{drag} = \frac{1}{2}\rho Cd(w * \Delta L)(L * \omega)^2$$

$$F_{drag} = \frac{1}{2}\rho C d w \omega^2 L^2 \Delta L$$

>Integrate with respect to ΔL>

$$F_{drag,tot} = \frac{1}{6}\rho C d w \omega^2 L^3$$

- With $\rho = 997\ \frac{kg}{m^3}$, $C_d = 1.15$, $w = 3\ in$, $\omega = 62.83$, and $L = 6\ in$:

$$F_{drag,angular} = 205\ N$$

This force follows a cubic distribution, so estimating it as a point load for torque calculations will be done 4/5 down the distance of the paddle. Notably, this is exactly one third of the total of 615 N initially assumed with the design of the locomotion system. As such, all internal components have a built-in safety factor because of the lower real torque.

Paddle & Hinge Stresses

With the high paddling rate comes a high resultant drag forces and torques applied directly to the paddles. Resources for calculating drag and stress concentrations can be difficult to find for such a specific purpose, so efforts have been made to estimate both using known methods.

Hinge Stress

To ensure that the hinges on the paddles could handle the required forces, each rung on the piano hinges were assumed to be four rectangular curved beams under equivalent loads. This calculation is a standard beam stress calculation, as shown in Figure .

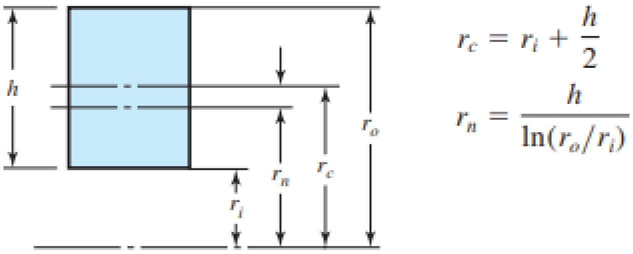


Figure 32. Curved Beam with rectangular cross section (Budynas, p. 135)

$$r_n = \frac{h}{\ln\left(\frac{r_o}{r_i}\right)}$$

$$r_c = r_i + \frac{h}{2}$$

$$e = r_c - r_n$$

$$M = F \times r_i$$

$$M_{distributed} = \frac{M}{6}$$

$$\sigma_i = \frac{M_{distributed}c}{Aer_i}$$

With $F = 615\ N,\ F = 615\ N$, $r_i = 0.047\ in, r_o = 0.087\ in$,$A = (.04)(2) = 0.08\ in^2$, $e = 0.002\ in,$ and $h = 0.04\ in$

$$M_{distributed} = \frac{615\ N\ \times 0.225\ \frac{lb}{N} \times .047\ in}{6\ Joints} = 0.54\ lb * in$$

$$\sigma_i = \frac{0.54\ lb * in \times 0.018\ in}{0.08\ in^2 \times 0.002\ in \times .047\ in} = 1292\ psi \ll \sigma_y$$

With a yield strength of 30,000 psi the 304 stainless steel hinges are well within the safe limit for stress.

Paddle Face Deflection

$$\delta_{max} = \frac{Pa^2}{6EI}(3l - a)$$

$$I = \frac{bh^3}{12}$$

- With $h = 0.02\ in, b = 3\ in, l = 6\ in, P = 615\ N = 138\ lbf, E = 10{,}500\ psi:$

$$\delta_{max} = 0.00087\ in$$

With the use of fiberglass, the maximum deflection on the paddles will be negligible.

Paddle Face Stress

Stress concentrations within the paddle face was difficult to arithmetically estimate as few resources exist regarding stress concentrations for this application. In contrast to previous methods, we opted to utilize the built-in stress simulator within Solidworks to find internal stress values. The results of this simulation can be found in Figure .

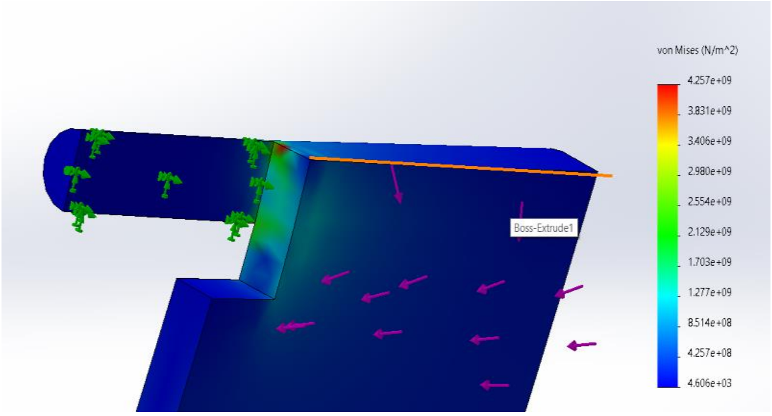


Figure 33. Stress concentration between paddle and shaft

Initial simulations suggest that the stress concentration between the paddle face and mounting shaft pose a potential risk of deformation or yielding. As such, we took steps to minimize the potential stress concentrations by modeling and simulating a separate paddle model with a 3-d printed ABS plastic support. Simulations suggested that this would reduce the maximum stress concentrations well below the yield strength of structural carbon fiber. See Figure for more details.

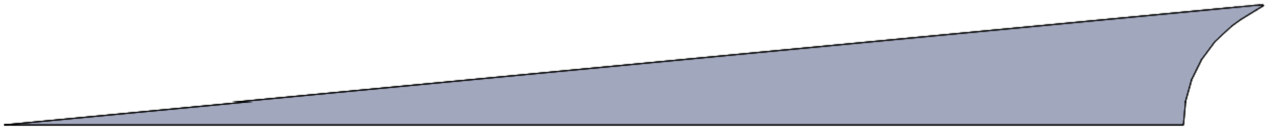


Figure 34. Shape of possible deformation pattern

Battery Selection

With the requirement of approximately 30 minutes of battery life, we had to balance the draw of the electric motors with the size of the battery. One battery would be supplying an estimated 45.5 A of power from the following components:

- Brushless motor: 45 A
- Arduino logic and sensors: <1 A
- Total: <46 A

The second battery will be supplying power for the following components:

- Brushless motor: 45 A
- Water pump: 0.3 A
- Servos: 2 A
- Total: 47 A

Battery life can be found with the following equation:

$$Battery\ Life\ [min] = \frac{Capacity\ [Amp * Hour]}{Discharge\ [Amp]} \times 60 \frac{[min]}{[Hour]}$$

- With $Capacity = 22\ Amp * Hour, Discharge = 47\ A$ and $46\ A$

$$Battery\ Life = 28.97 \min and\ 29.1 \min$$

With this in mind, we selected the Liperior brand 22,000 mAh, four cell, 12c discharge lithium polymer battery. It offers a combination of compact size, capacity, and discharge rate that fit the needs of this project. When we ordered our second battery, we had to choose a different supplier due to lack of inventory. However, we still got the same type of LiPo battery, just a different brand.

Figure 35. Lithium Polymer Batteries

Voltage Reading

Since monitoring the drainage of the batteries is vital to safely operating the design, we decided to include a voltage reader on each battery that feeds analog voltage information directly to the Arduino microprocessor. This reader will measure battery voltage which scales directly with the total discharge of the batteries. This comes in the form of a voltage divider across the leads for both batteries. Since the Arduino analog pins can only accept inputs of up to five volts, the voltage divider was required to step down from the 16.8 maximum battery voltage to less than five volts. The following covers the calculations for sizing the resistors.

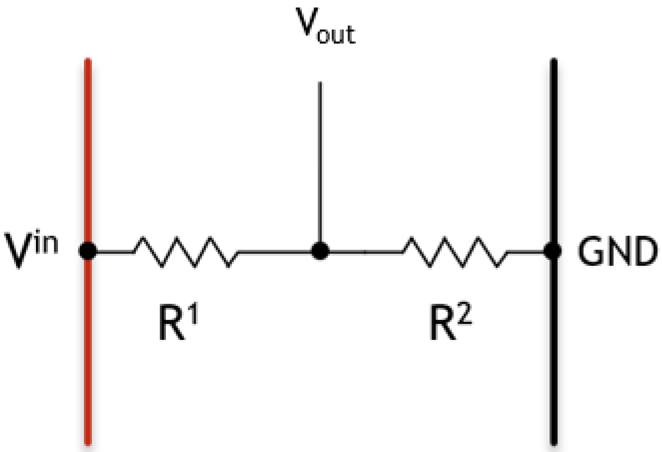


Figure 36. Voltage Divider diagram

$$P = \frac{V_{in}^2}{(R_1 + R_2)}$$

$$V_{out} = V_{in}\frac{R_2}{(R_1 + R_2)}$$

- With the constraints of $P \le 0.25\ W$, $V_{in} \le 4.5\ V$, and $V_{in} = 16.8\ V$

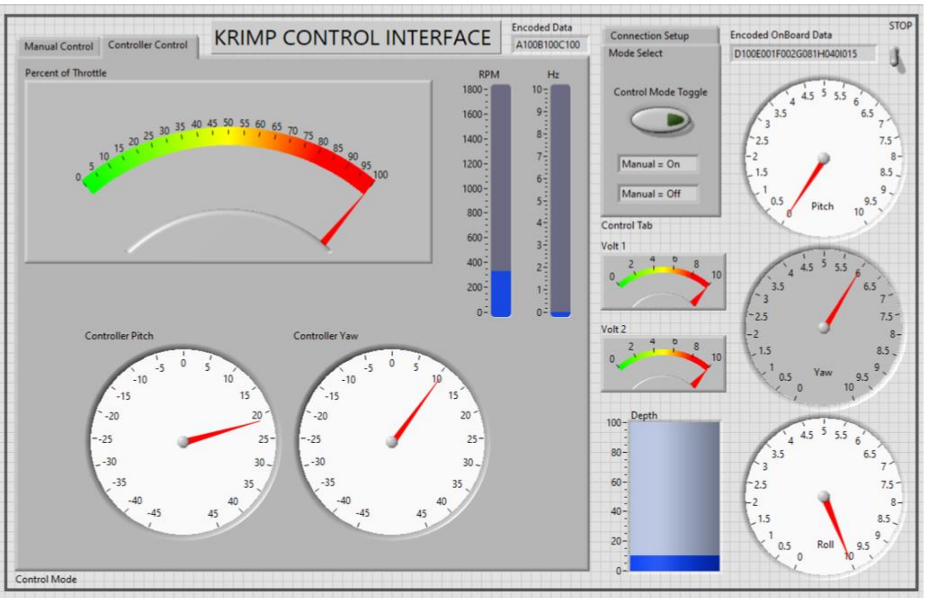
$$R_1 = 1000\ \Omega \text{ and } R_2 = 300\ \Omega$$

Each of these resistors is already available and as such do not need to be purchased. With one voltage divider attached to each of the battery terminals there will be a wire carrying V_{in} for each of the batteries to an Arduino analog pin.

Logic

The control of the vehicle relies on components on both the inside and outside. The process begins with the pilot operating a joystick with throttle, pitch, and yaw. These input commands are then taken by the computer, displayed on a Graphic User Interface (GUI) in LabVIEW, and then packaged via LabVIEW and sent to the Arduino using a USB chord. The Arduino receives the information, unpacks the commands, and sends them via tether to the onboard I^{2}C converter. A tether is used for this due to a lack of time, total autonomous control would have been very difficult to achieve. Once converted, the data is passed to its appropriate device based on the commands from the on-land Arduino. The throttle, pitch, and yaw are handed over to the PCA which directs these three commands via PWM to the servos and motors. The throttle is sent to the SPARK MAX Motor Controller which then gives the voltage and amps to achieve the necessary speed. The servos receive the information necessary to control yaw and pitch. Also onboard the vehicle is a BNO055 and Bar30 High Resolution Depth Sensor. The BNO055 tracks the acceleration in any plane and sends this information back to the Arduino. The Arduino then takes this information and can control the servos to re-right itself. The Bar30 simply takes the depth and sends it back to the GUI. Figure shows the GUI control and data display on the user's computer, and Figure shows the diagram for the logic system.

The operators have the choice of an automatic and manual mode. Automatic mode is when the user inputs a given RPM into the GUI, and the vehicle automatically adjusts to reach the desired speed without needing an input throttle from the operator. Manual mode is when the operator gives the system an input throttle via the remote controller, which then is passed to the GUI, interpreted, then an RPM is passed to the rest of the system.



Encoded Data: A100B100C100

Encoded OnBoard Data: D100E001F002G081H040I015

Manual = On

Manual = Off

Figure 37. LabVIEW GUI control and data display

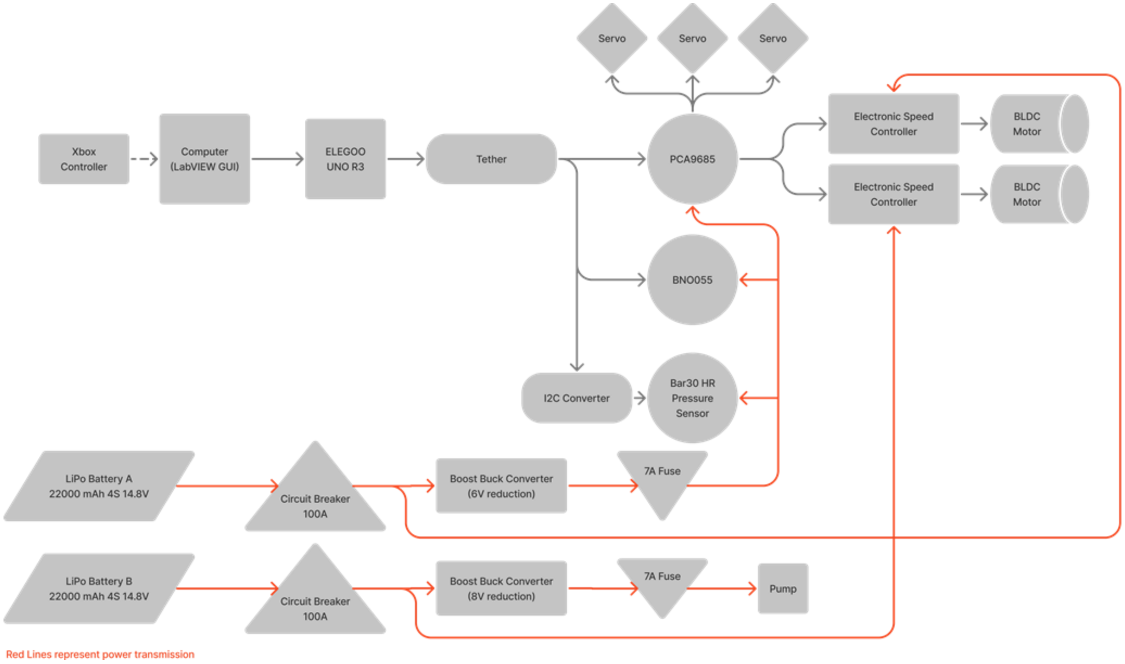


Figure 38. Diagram of how logic communication and data transfer works

Communication

The main form of communication is I^2C communication. The Arduino is on land and sends data via the neutrally buoyant tether to the appropriate devices (motor controller, PCA, BNO, sensors). There is another conversion to 3.3I^2C while moving to the Bar30 Pressure Sensor. The PCA9685 communicates with all its modules with Pulse Width Modulation (PWM).

Code and Coding

The main coding language used will be LabVIEW. A LabVIEW GUI displays the different throttles, inputted RPMs, and the data from the sensors onboard the vehicle. The computer will be using this to package the necessary instructions, send them via USB to the on-land Arduino, then via tether the communication is passed to the devices onboard. The Arduino will be the means of communication for data receiving and sending. The figures below show the loops necessary for the motors and servos.

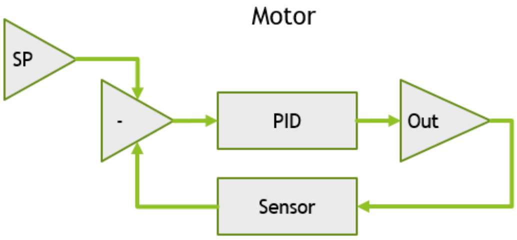


Figure 39. Motor Control Loop

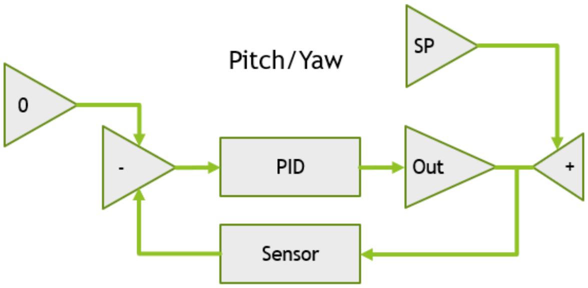


Figure 40. Pitch and yaw control loop with servos

Electronics

The electronics system starts with two 22000 mAh 4s 14.8V batteries on either side of the vehicle's body. The battery on the right powers all available sensors and the servo control board. The battery on the left powers the PCA9685, and pump. Each battery’s primary purpose, however, is to power the brushless motors. The servos are powered and controlled via the PCA9685 servo controller. To prevent module damage by overvoltage, each battery first connects to a circuit breaker. After the circuit breaker, the line splits with one lead powering the motors and the other powering the sensors, servos, and servo controller. All sensitive components are protected by fuses.

The surface houses all controls in the form of two Arduinos communicating via I^2C signaling. One Arduino sends command signals to the servos and motors while simultaneously receiving and sending sensor data. The second Arduino running LabVIEW receives date from the first Arduino and displays it on a connected computer.

The figure below shows the general wiring system described within the main body.

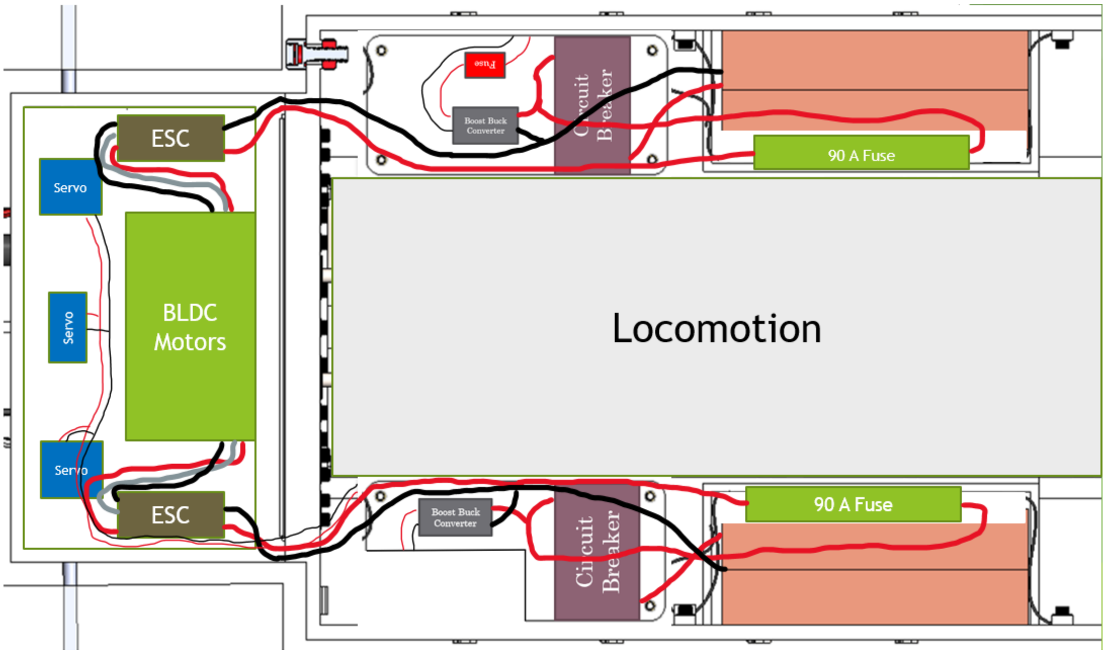
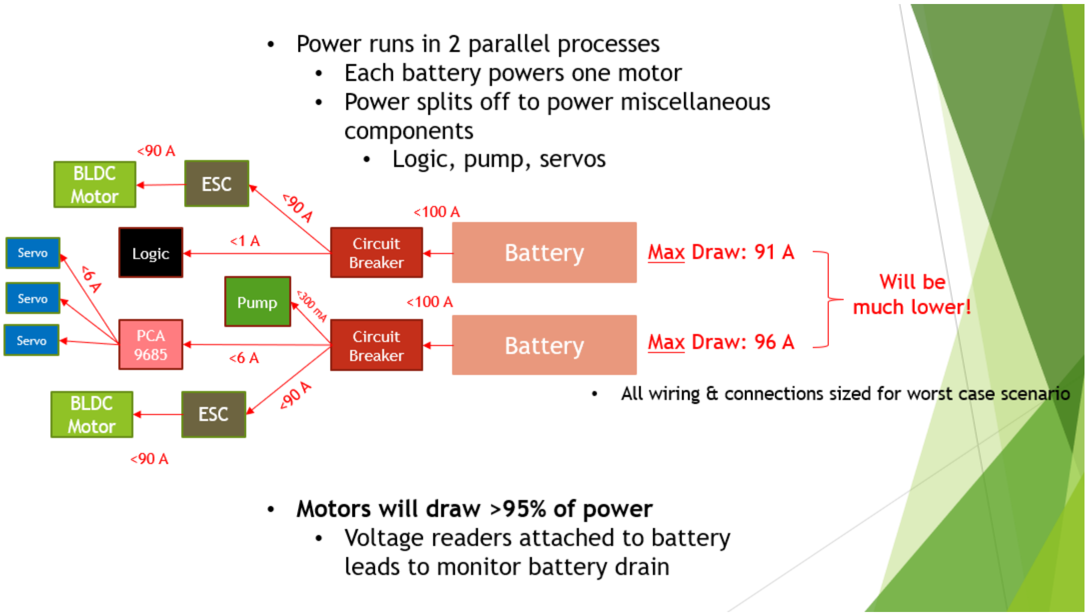


Figure 41. Power delivery for the electronics system



- Power runs in 2 parallel processes
  - Each battery powers one motor
  - Power splits off to power miscellaneous components
    - Logic, pump, servos

- All wiring & connections sized for worst case scenario

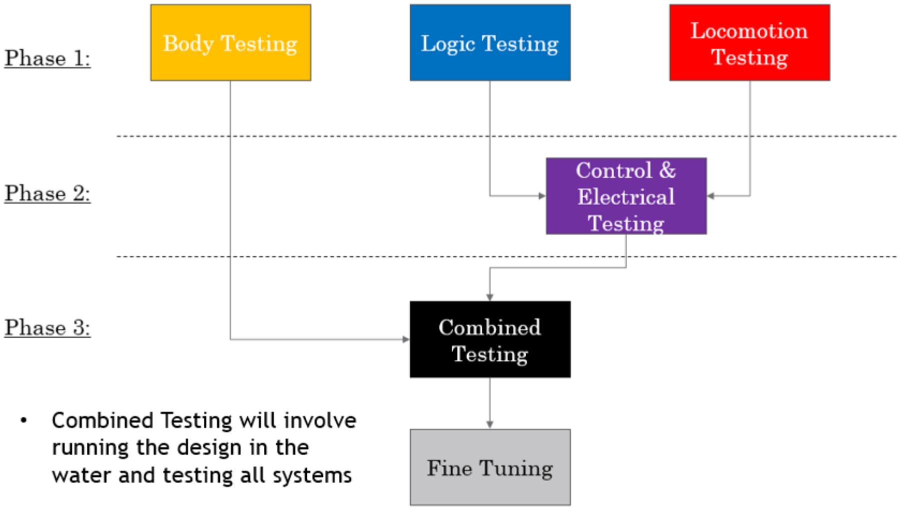
- **Motors will draw >95% of power**
  - Voltage readers attached to battery leads to monitor battery drain

Figure 42. Power transmission

The figure above shows the flow of amps across the entirety of the system. The largest amount of amperage flows into the ESCs which then power and control the brushless motors. Due to this, the batteries will be able to last at least 30 mins, which was the time trial requirement given to us.

TESTING AND QUALITY PLAN

Our testing plan was split up into three main phases. The first phase consisted of a separate body, logic, and locomotion testing, which allowed for each subsystem to be tested for functionality. The second phase paired the logic and locomotion together, to check for appropriate powering of the device. Lastly, phase three combined all 3 main subsystems together for the final testing of the design.



- Combined Testing will involve running the design in the water and testing all systems

Figure 43. Diagram of three main testing phases

Phase 1: Individual Testing

Phase 1.1: Body

The body testing consisted of first filling the body with water to check for leaks. Leaks found were sealed with silicone and allowed to fully set and dry. The body underwent multiple tests to seal all leaks found, which were on the front rounded edge of the body and from one waterproof bearing. Once confirmed that the acrylic weld, epoxy, and silicone was maintaining a watertight seal, the lid and gasket material was incorporated into the test. We then tested waterproof ability by sealing the body with the lid and placing the hull in the water and submerging it for a few minutes. The body was then removed from the water and checked for any leaks. This process was repeated several times as well, and each leak was fixed over iterative tests. If leaks were found, necessary measures and reapplication of silicone were performed, as with the first waterproof test. The places where leaks seemed to occur most with the second test were the surface seal, inner gaskets, and the front rounded edge. All leaks were found, secured, and tested to ensure a waterproof body. Once the body passed this test, we applied a final layer of flex seal as an extra precaution to ensure the body remained fully waterproof.

While body testing was going on, we also tested the ability of the cooling system to pump water without having any leaks inside. The pump was run for 30 minutes, and the tubing monitored for leaks.

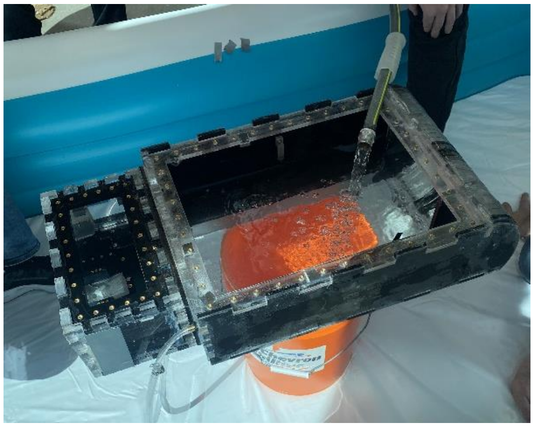


Figure 44. Initial waterproof test of the body

Phase 1.2: Logic

A GUI in LabVIEW was created to display and begin the transfer of all the data. All the pieces were then connected, the joystick to the computer, the computer via the USB to the Arduino, and finally the Arduino to the motor controllers, servo controller, and sensors via I^2C. The commands were sent back and forth to make sure the transfer of data was correct and uninhibited. A more in-depth module testing occurred in Phase 2. This phase was critical in making sure the data transmission and messaging was working correctly and transferring data.

Testing of the tether adaptor was also performed during this phase once the logic system was assured to work. To do this, we performed a waterproof check on the Wet link penetrator that allowed the tether into the body without allowing water to pass through. Once this device was proven to be waterproof and sealed, the tether was attached and secured.

Phase 1.3: Locomotion

The locomotion testing was one of the most critical and in-depth phases. It started with a single link of our fully designed worm powered system. We created a test bed to begin this phase and prove that our designed locomotion system would work and produce the appropriate output motion. This test existed to make sure the locomotion idea works in the first place before purchasing all parts. Once the motion was achieved and proven to work, the entire locomotion system was ordered and then built. The motors were then powered, and the temperature, torque, and general reliability of the system were determined. This part of the phase showed how the motors would drive the drive shaft of the locomotion system, as well as the gear meshing, functionality, and capabilities under different speeds. After adjusting and fastening all parts of the locomotion system and ensuring the long-term functionality, the project testing moved onto the next phase.

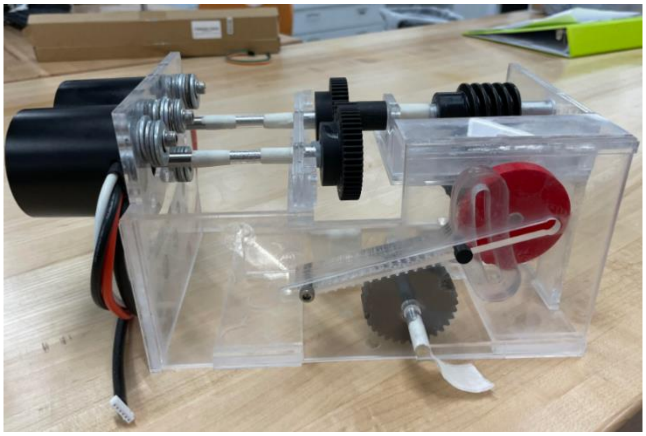


Figure 45. Locomotion test bed

Phase 2: Control & Electrical Testing

In this phase, the logic and locomotion system were put together and evaluated for efficacy. The controller was used to see if the motors and servos responded to inputs. The BNO055 was also manipulated to see if the servos were controlling the fins and responding appropriately to the given body tilts. The depth sensor was tested to ensure that it sensed when it was in water and ensure it could send the appropriate data back to the GUI. The thermal switches were tested with a heat gun to make sure that, when they sensed heat in the body, they would turn the water pump on and start the cooling system up. Once all systems were seen to work together, the internals were ready to be inserted into the body. To make this part easier, our team created two electronics platforms out of acrylic to mount the devices on. Velcro tape held each device and sensor in its appropriate place inside the body and helped assure nothing would shift during the vehicles run time. These platforms worked well and ensured reduced clutter once all parts were inserted.

Phase 3: Combined Testing

This phase was the final test and one of the most important. This test showed that our waterproofing and individual subsystems all worked together as intended. The locomotion, logic, and electrical systems were all placed within the body. The connections and movements were then assessed on the land to start. The controller was first used to test the electronic functionality and ability to move the drive shafts and paddles. Then the body was tilted and rotated to make sure the BNO055 sensor still worked and moved the control surfaces as necessary. Once the systems were all proven to still work, the body was then introduced to water and full testing and fine tuning of positioning began. Any weight changes/movements, servo positioning, or any other necessary fixes were made during this time to ensure the vehicle was operational for the EXPO and final delivery.

Testing Results

After full water and movement testing on our design, it was proven that our device was waterproof, swam like a shrimp with correct metachronal paddling, and could stabilize itself and turn with the control surfaces on the back of the body. When sent an RPM through the LabVIEW GUI on the computer, the device sped up and slowed down as intended.

AS BUILT DESIGN OVERVIEW

Locomotion System

The locomotion system remains is almost identical to the original design. Shims were added to give the worm and worm gears proper pitch diameter gap. Subsequently the key mechanism had to have some slight changes to compensate for the minor changes. The final system is pictured below:

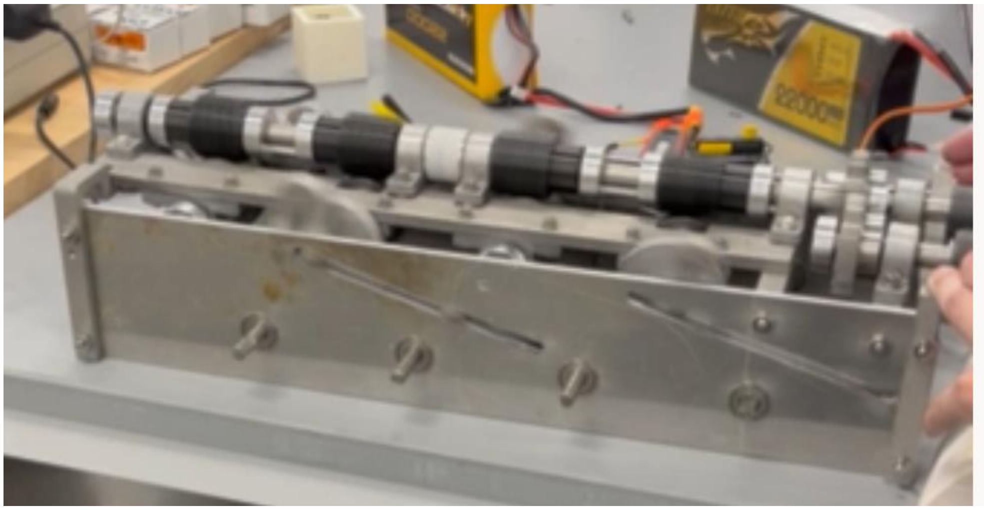


Figure 46. Locomotion System as built separate from the body

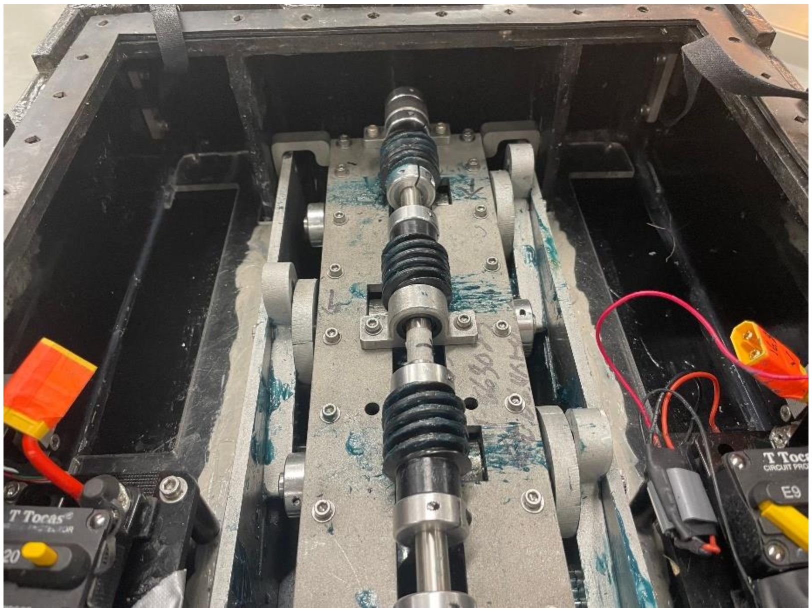


Figure 47. Locomotion Installed in body

Electronic System

The electrical system is divided between surface components and subsurface components. The surface components consists of a computer, two Arduinos, and a connecting ROV tether. One Arduino running C++ communicates with the on-board sensors and controllers via I^{2}C communication.

Commands are sent down the tether to the motor and servo controllers which function as throttle and orientation control. Sensor data is gathered in the body and sent back to the surface through the tether.

The second Arduino using LabVIEW communicates with the first Arduino in an I^2C master-slave relationship with the second Arduino functioning as the master. Sensor and control data is transferred between the two.

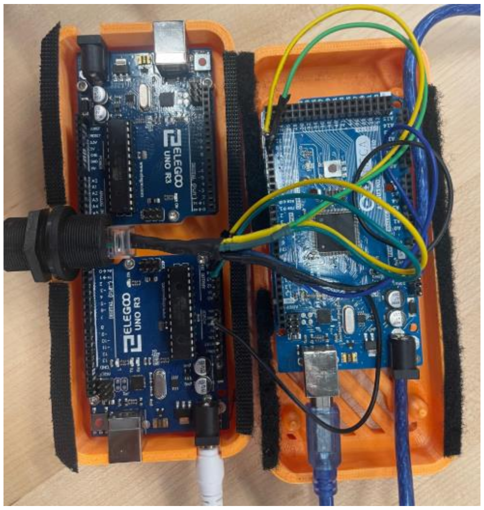


Figure 48. Master & Slave Arduino Surface Control

On the body itself, the electrical system is split into two halves with one battery powering one motor each. A small amount of power is drained from both sides to power miscellaneous components such as the coolant pump and sensors.

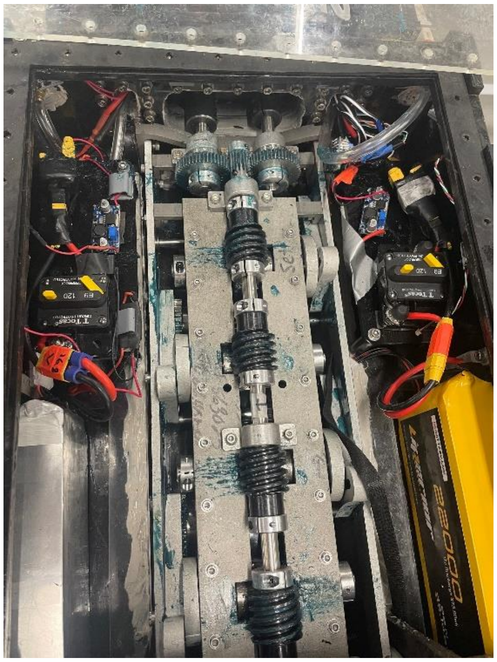


Figure 49. Electrical System Incorporated into Main Compartment

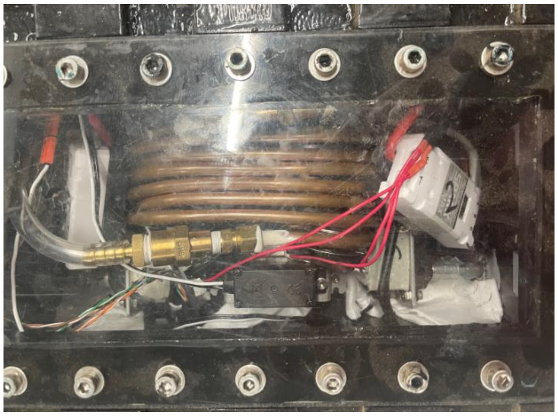


Figure 50. Electrical System Incorporated into Rear Compartment

Body

As detailed the body was built out of many acrylic panels welded together. Once the body was fully assembled, it was coated in a rubberized, waterproof material. The body didn't undergo any other design changes and remains very similar to the theoretical design. The body is shown in its as built state below.

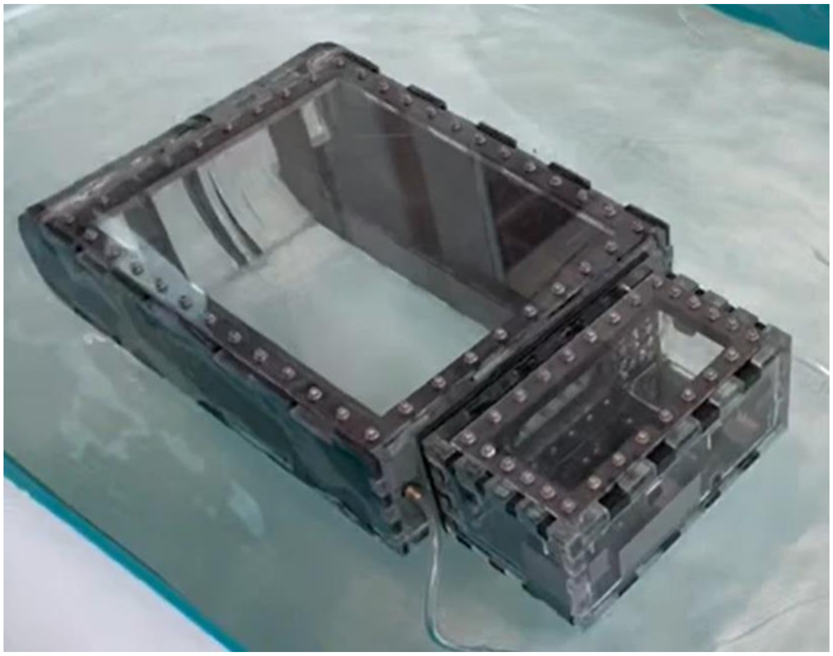


Figure 51. Body with no Rubberized Coating

Overall Design:

The drone performs its tasks as desired and set out in the design phases. As this was a large and ambitious project, we weren't able to fully test the capabilities of the drone due to lack of time, resources, and a testable water source. The drone achieves adjustable phase-lag-metachronal paddling. The robot needs more testing and improved body design before fully powering the locomotion system and testing at 10 Hz. This is due to a multitude of factors. With an acrylic body, if the gear train were to seize, all torque would be transmitted to the body and can lead to cracks in the hull. The body should be tested in a controlled environment to quantify the vibrations the locomotion system produces and its effect of the frame and body overall.

The electrical system works as intended. The user can switch between controller or direct inputs which are then sent to the PCA on board. The control surfaces work and allow for correction of the motion during operation. Finally, the battery life is longer than expected as the motors haven't been operated at their maximum capabilities due to the constraints listed above.

Team KRIMP successfully built a bio-inspired underwater vehicle that swims utilizing metachronal motion.

Figure 52. Final Krimp Design

COST BREAKDOWN

The project incorporates an advanced locomotion system that converts constant rotation into metachronal paddling motion. Along with the locomotion system there was also various electronic components to help control the movement, and materials that helped ensure proper waterproofing of the body. Upon the conclusion of the CDR report we saw our estimated cost to be roughly $5,567.35 which comes well over the allotted $4,000 budget. After some subtle redesigning of the product and some optimizing of the materials cost, we were able to get the final cost down to $4,072.19.

Locomotion System

5	Part Numb	lcMaster Part Num	Description	System	Price	Quantity	Total Price	Buy or Make	ed/Man
41	20002	2664N516	Metal Gear - 48 mm pitch	20000	$81.55	4	$326.20	Buy	YES
42	20004	A18121800ux0688	Set Screw Shaft Coupling 8mm 2 pack	20000	$9.99	6	$59.94	Buy	YES
43	20005	57545K643	Steel Worm	20000	$29.38	4	$117.52	Buy	YES
44	20008	2664N536	Metal Gear - 15mm Pitch	20000	$28.72	1	$28.72	Buy	YES
45	20009	5972K501	Ball bearing 8mm	20000	$14.33	8	$114.64	Buy	YES
54	20018	CSK8P	One way Ball Bearing Clutch 8mm	20000	$16.99	4	$67.96	Buy	YES
55	20019	57545K821	Metal Worm Gear	20000	$30.66	4	$122.64	Buy	YES
56	20020	98380A540	416 SteelDowel Pin1/4"D, 3/4"L(10Pack)	20000	$12.93	1	$12.93	Buy	YES
59	20025	2664N554	Metal Gear - 50 mm pitch	20000	$69.83	2	$139.66	Buy	YES
60	20026	3084K92	Clamping Shaft Coupling 12mm x 8mm	20000	$44.79	2	$89.58	Buy	YES
75	20037	NA	Paddle Shaft Final*	20000	$0.00	4	$0.00	Make	YES
76	20038	NA	Paddle Shaft Final Opp*	20000	$0.00	4	$0.00	Make	YES
77	20039	NA	Half Drive Shaft*	20000	$0.00	1	$0.00	Make	YES
78	20040	NA	Half Drive Shaft Opp*	20000	$0.00	1	$0.00	Make	YES
79	20041	NA	H Frame*	20000	$0.00	1	$0.00	Make	YES
80	20042	NA	H Frame Opp*	20000	$0.00	1	$0.00	Make	YES
81	20043	NA	Rot 2 Trans Bracket*	20000	$0.00	1	$0.00	Make	YES
82	20044	NA	Rot 2 Trans Bracket Opp*	20000	$0.00	1	$0.00	Make	YES
83	20045	NA	Key Side Bracket*	20000	$0.00	1	$0.00	Make	YES
84	20046	NA	Key Side Bracket Opp*	20000	$0.00	1	$0.00	Make	YES
85	20047	NA	Mid Frame*	20000	$0.00	1	$0.00	Make	YES
86	20048	NA	Mid Frame 2*	20000	$0.00	1	$0.00	Make	YES
87	20050	NA	Key Mechanicism	20000	$0.00	2	$0.00	Make	YES
88	20051	NA	Key Mechanicism Opp	20000	$0.00	2	$0.00	Make	YES
89	20052	NA	Rot 2 Trans*	20000	$0.00	2	$0.00	Make	YES
90	20053	NA	Rot 2 Trans Opp*	20000	$0.00	2	$0.00	Make	YES
91	20054	NA	Outer Hub	20000	$0.00	4	$0.00	Make	YES
92	20055	NA	Paddle Shaft Placement	20000	$0.00	1	$0.00	Make	YES
93	20056	NA	Half Shaft*	20000	$0.00	8	$0.00	Make	YES
94	20057	NA	Upper Paddle	20000	$0.00	8	$0.00	Make	YES
95	20058	NA	Lower Paddle	20000	$0.00	8	$0.00	Make	YES
96	20059	NA	Motor Mount	20000	$0.00	1	$0.00	Make	YES
97	20060	NA	Motor Shaft	20000	$0.00	2	$0.00	Make	YES
107	20070	NA	Vertical Fin	20000	$0.00	1	$0.00	Make	YES
108	20071	NA	Horizontal Fin	20000	$0.00	2	$0.00	Make	YES
109	20072	NA	Servo Shaft*	20000	$0.00	3	$0.00	Make	YES
111	20073	Refractory Anchors Inc	1/4" Stainless Steel 304 13"x18"	20000	$19.45	1	$19.45	Buy	YES
112	20074	Refractory Anchors Inc	1/2" Stainless Steel 304 9"x10"	20000	$25.50	1	$25.50	Buy	YES
113	20000	7398K216	12mm Key Shaft 400mm	20000	$27.86	4	$111.44	Buy	YES
114	20000	1272T38	304 Rod Stock (3Ft)	20000	$23.63	1	$23.63	Buy	YES
115	20000	1265K64	8mm Rotary Shaft(Raw)200mm	20000	$23.00	1	$23.00	Buy	YES
116	20075	1265K66	8mm Rotary Shaft(Raw)400 mm	20000	$38.90	2	$77.80	Buy	YES
117	20079	8537K25	1/4 Fiberglass Sheet(Raw)12"x12"	20000	$27.09	1	$27.09	Buy	YES
131	20081	8982K137	Motor Mount	20000	$21.27	1	$21.27	Buy	YES
133	20000	9506T4	8mm Shaft Collar	20000	$5.10	5	$25.50	Buy	YES
134	20000	9506T6	12 mm Shaft Collar	20000	$6.43	21	$135.03	Buy	YES
135	20000	2820T55	12 mm Dry Run Bearing	20000	$18.28	14	$255.92	Buy	YES
136	20000	1792A44	Piano Hinges 3ft	20000	$40.14	1	$40.14	Buy	YES
140	20000	90457A100	Key Stock 2mmx2mm	20000	$11.97	1	$11.97	Buy	YES
141	20000	90457A120	Key Stock 4mmx4mm	20000	$17.56	2	$35.12	Buy	YES
143	20000	1272T38	Stainless steel rod	20000	$14.18	1	$14.18	Buy	YES
144	20000	7398K217	12 mm Key shaft 1000mm	20000	$69.40	1	$69.40	Buy	YES
145	20000	97447a135	Rivets	20000	$12.82	1	$12.82	Buy	YES
146	20000	174036	Servo Bolts	20000	$0.43	10	$4.30	Buy	YES
147	20000	170984	Servo Nuts	20000	$0.28	10	$2.80	Buy	YES

Figure 53. Locomotion B.O.M.

The locomotion system can be broken down into various components, with the main ones being different types of gears shaft that all serve to make the drive train assembly. When looking at the total cost alone for just the locomotion system the final price came out to be $2,016.15

Body

Part Numbe	McMaster Part Numbe	Description	System	Price	Quantity	Total Price	Buy or Make	ed/Manu
30002	9455K62	Neoprene Gasket(60A)(Raw)	30000	$17.83	2	$35.66	Buy	YES
30006	NA	XTC-3D Coating	30000	$40.06	1	$40.06	Buy	YES
30008	NA	Body*	30000	$0.00	1	$0.00	Make	YES
30009	NA	Body Rear Body*	30000	$0.00	1	$0.00	Make	YES
30010	NA	Connecting Gasket*	30000	$0.00	1	$0.00	Make	YES
30011	NA	Main Gasket*	30000	$0.00	1	$0.00	Make	YES
30012	NA	Rear Cover*	30000	$0.00	1	$0.00	Make	YES
30013	NA	Rear Gasket*	30000	$0.00	1	$0.00	Make	YES
30014	NA	Velcro Flipper*	30000	$0.00	2	$0.00	Make	YES
30015	NA	Velcro Press*	30000	$0.00	2	$0.00	Make	YES
30016	9402T51	1/2 Velcro Strap 15Ft	30000	$6.41	1	$6.41	Buy	YES
30017	Refractory Anchors Inc	1/2" Stainless Steel 304 8"x22"	30000	$42.36	2	$84.72	Buy	YES
30018	WLP-M10-7.5MM-HC-R1-RP	WetLink Penetrator	30000	$12.00	1	$12.00	Buy	YES
30000	7517A4	Acrylic Weld	30000	$20.41	1	$20.41	Buy	YES

Figure 54. Body B.O.M.

The next section is body design, with much of the components being centered around waterproofing of the body the final price sits at $199.26.

Electronics

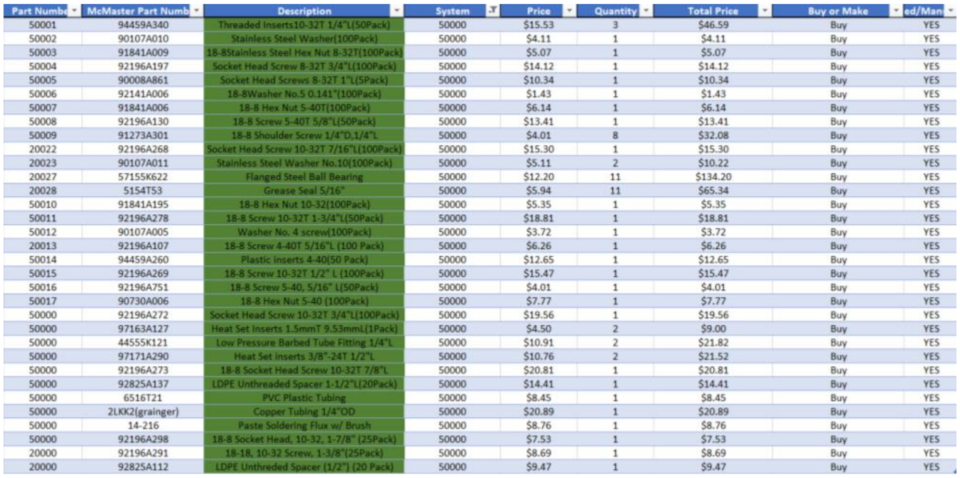
The electronics systems consisted of mainly of two different subsystems, one to help regulate and protect the system power components and the other to control the logic needed to have control of the movement. Altogether we saw a cost of $1,092.05 for all the electronic system.

Part Numbe	McMaster Part Numb	Description	System	Price	Quantity	Total Price	Buy or Make	ed/Man
10001	Amazon Link	Elegoo Uno R3	10000	$18.99	0	$0.00	Buy	YES
10002	Amazon Link	CAN Shield	10000	$33.99	0	$0.00	Buy	YES
10003	BNO055	BNO055	10000	$34.95	1	$34.95	Buy	YES
10004	Robotshop Link	PCA9685	10000	$9.99	1	$9.99	Buy	YES
10005	USB To CAN Converter	USB to CAN Converter	10000	$34.99	1	$34.99	Buy	YES
10006	DB9	DaFuRui DB9	10000	$15.99	1	$15.99	Buy	YES
10007	Bar30 UHR Depth Reader	Bar30 Depth Sensor	10000	$72.00	1	$72.00	Buy	YES
10008	C Level Converter (for Bar0	Bar30 I2C level converter	10000	$20.00	1	$20.00	Buy	YES
10009	NA	PlayStation Controller	10000	$0.00	0	$0.00	Buy	YES
10010	2 m Neutrally Buoyant Teth	ROV Tether (7m)	10000	$35.00	1	$35.00	Buy	YES
10011	REV-21-1650 (RevRobotics	Neo Brushless Motor (Dr. Bai)	10000		2	$0.00	Buy	YES
10012	REV-11-2158 (RevRobotics	SPARK MAX Controller (Dr. Bai)	10000		2	$0.00	Buy	YES
10013	PCB Board	PCB Breadboard	10000	$12.99	1	$12.99	Buy	YES
10101	REV-41-1097 (RevRobotics	Smart Robot Servo	10000	$28.00	3	$84.00	Buy	YES
10201	4s 22000 mAh Battery	22000 mAh 4S LiPo Battery	10000	$343.89	1	$343.89	Buy	YES
10202	100 A Circuit Breaker	120A Auto Reset Circuit Breaker	10000	$26.99	2	$53.98	Buy	YES
10203	LiPo Charger	LiPo Charger	10000	$126.97	1	$126.97	Buy	YES
10204	LiPo Safety Bag	LiPo Bag	10000	$10.99	2	$21.98	Buy	YES
10205	10 Gauge	10 AWG Wire (Black & Red)	10000	$35.99	1	$35.99	Buy	YES
10206	Boost Buck Converter	LM2596 (pack of 6)	10000	$10.99	1	$10.99	Buy	YES
10208	7A Slow Blow Fuse	7 A Slow Blow Fuse (pack of 10)	10000	$7.99	1	$7.99	Buy	YES
10209	7A Slow Blow Fuse Holder	7 A Slow Blow Fuse Holder (pack of 5)	10000	$6.49	1	$6.49	Buy	YES
10210	1A fast blow fuse	1 A Fast Blow Fuse (pack of 5)	10000	$7.25	1	$7.25	Buy	YES
10211	1A fast blow fuse holder	1 A Fast Blow Fuse Holder	10000	$6.99	1	$6.99	Buy	YES
10212	Xt90 Anti-Spark Connector	XT90 Anti Spark Connectors (pack of 10)	10000	$13.86	1	$13.86	Buy	YES
10213	xt90 y-splitter	XT-90 Y-Splitter	10000	$14.99	1	$14.99	Buy	YES
10212	2,3,4 Pin Connectors	2,3,4 Pin Connectors	10000	$9.99	1	$9.99	Buy	YES
10215	12-10 AWG Connector	12-10 AWG Connector	10000	$9.99	1	$9.99	Buy	YES
10216	NA	1k Ohm Resistor	10000	$0.00	2	$0.00	NA	YES
10217	Thermal Switch	Thermal switches	10000	$14.95	2	$29.90	Buy	YES
10218	r/dp/B07YRRCR9G/ref=sr_1	xt60 to xt90 Connectors	10000	$8.50	1	$8.50	Buy	YES
10219	8026K9	Anderson connector (pack of 5)	10000	$0.00	1	$0.00	Buy	YES
10218	NA	330 Ohm Resister	10000	$0.00	1	$0.00	NA	YES
10220	NA	LiPo Voltage Checker Alarm	10000	$0.00	2	$0.00	NA	YES
10102	REV-41-1485	15 mm Bent Servo Bracket	10000	$5.00	1	$5.00	Buy	YES
10103	REV-41-1682	15 mm Metal Outside Channel	10000	$5.00	1	$5.00	Buy	YES
10000	6605K23	Hook and Loop Cable Ties 6"(10 Pack)	10000	$6.99	1	$6.99	Buy	YES
10000	54885K13	Corrugated Steel Sleeving 10ft	10000	$10.30	1	$10.30	Buy	YES
10000	7565K32	Cable Holders (25Pack)	10000	$10.48	1	$10.48	Buy	YES
10000	8026k9	Pin-to-Pin Connectors	10000	$6.62	1	$6.62	Buy	YES
10000	WLP-SEAL-7.5mm	Wetlink Penetrator Seals	10000	$18.00	1	$18.00	Buy	YES

Figure 55. Electronics B.O.M.

Hardware

For hardware, we needed various screws, nuts, and other miscellaneous items. These were used ultimately to put the body and inner framework together. Altogether our hardware cost came out to be $603.30



Part Numbe	McMaster Part Numb	Description	System	Price	Quantity	Total Price	Buy or Make	ed/Man
50001	94459A340	Threaded Inserts10-32T 1/4"L(50Pack)	50000	$15.53	3	$46.59	Buy	YES
50002	90107A010	Stainless Steel Washer(100Pack)	50000	$4.11	1	$4.11	Buy	YES
50003	91841A009	18-8Stainless Steel Hex Nut 8-32T(100Pack)	50000	$5.07	1	$5.07	Buy	YES
50004	92196A197	Socket Head Screw 8-32T 3/4"L(100Pack)	50000	$14.12	1	$14.12	Buy	YES
50005	90008A861	Socket Head Screws 8-32T 1"L(5Pack)	50000	$10.34	1	$10.34	Buy	YES
50006	92141A006	18-8Washer No.5 0.141"(100Pack)	50000	$1.43	1	$1.43	Buy	YES
50007	91841A006	18-8 Hex Nut 5-40T(100Pack)	50000	$6.14	1	$6.14	Buy	YES
50008	92196A130	18-8 Screw 5-40T 5/8"L(50Pack)	50000	$13.41	1	$13.41	Buy	YES
50009	91273A301	18-8 Shoulder Screw 1/4"D,1/4"L	50000	$4.01	8	$32.08	Buy	YES
20022	92196A268	Socket Head Screw 10-32T 7/16"L(100Pack)	50000	$15.30	1	$15.30	Buy	YES
20023	90107A011	Stainless Steel Washer No.10(100Pack)	50000	$5.11	2	$10.22	Buy	YES
20027	57155K622	Flanged Steel Ball Bearing	50000	$12.20	11	$134.20	Buy	YES
20028	5154T53	Grease Seal 5/16"	50000	$5.94	11	$65.34	Buy	YES
50010	91841A195	18-8 Hex Nut 10-32(100Pack)	50000	$5.35	1	$5.35	Buy	YES
50011	92196A278	18-8 Screw 10-32T 1-3/4"L(50Pack)	50000	$18.81	1	$18.81	Buy	YES
50012	90107A005	Washer No. 4 screw(100Pack)	50000	$3.72	1	$3.72	Buy	YES
20013	92196A107	18-8 Screw 4-40T 5/16"L (100 Pack)	50000	$6.26	1	$6.26	Buy	YES
50014	94459A260	Plastic inserts 4-40(50 Pack)	50000	$12.65	1	$12.65	Buy	YES
50015	92196A269	18-8 Screw 10-32T 1/2" L (100Pack)	50000	$15.47	1	$15.47	Buy	YES
50016	92196A751	18-8 Screw 5-40, 5/16" L(50Pack)	50000	$4.01	1	$4.01	Buy	YES
50017	90730A006	18-8 Hex Nut 5-40 (100Pack)	50000	$7.77	1	$7.77	Buy	YES
50000	92196A272	Socket Head Screw 10-32T 3/4"L(100Pack)	50000	$19.56	1	$19.56	Buy	YES
50000	97163A127	Heat Set Inserts 1.5mmT 9.53mmL(1Pack)	50000	$4.50	2	$9.00	Buy	YES
50000	44555K121	Low Pressure Barbed Tube Fitting 1/4"L	50000	$10.91	2	$21.82	Buy	YES
50000	97171A290	Heat Set Inserts 3/8"-24T 1/2"L	50000	$10.76	2	$21.52	Buy	YES
50000	92196A273	18-8 Socket Head Screw 10-32T 7/8"L	50000	$20.81	1	$20.81	Buy	YES
50000	92825A137	LDPE Unthreaded Spacer 1-1/2"L(20Pack)	50000	$14.41	1	$14.41	Buy	YES
50000	6516T21	PVC Plastic Tubing	50000	$8.45	1	$8.45	Buy	YES
50000	2LKK2(grainger)	Copper Tubing 1/4"OD	50000	$20.89	1	$20.89	Buy	YES
50000	14-216	Paste Soldering Flux w/ Brush	50000	$8.76	1	$8.76	Buy	YES
50000	92196A298	18-8 Socket Head, 10-32, 1-7/8" (25Pack)	50000	$7.53	1	$7.53	Buy	YES
20000	92196A291	18-18, 10-32 Screw, 1-3/8"(25Pack)	50000	$8.69	1	$8.69	Buy	YES
20000	92825A112	LDPE Unthreded Spacer (1/2") (20 Pack)	50000	$9.47	1	$9.47	Buy	YES

Figure 56. Hardware B.O.M.

Total Cost

The final cost after all the items were purchased and the additional $162.16 of shipping charges came out to be $4072.92.

RISK MANAGEMENT

Due to the context of this project, several risk management strategies were adopted to minimize the risk to both the designers, potential users, and the design itself. Risks that have been identified with this project include:

- High current draw from the electrical motors
- Battery overdraws or overcharge and resultant fires
- Electrical fires from wiring
- Excessive internal heat
- Pinching from locomotion system
- Muscle strain from picking up design
- Drowning due to deep water
- Time and scheduling constraints
- Budget limitations
- Manufacturing and assembly errors
- Locomotion system functionality

Each of these potential risks have been individually considered and steps have been taken to minimize their resultant risk in both design and methodology.

Electrical

The risks related to battery overdraw and overcharge were both mitigated due to a selection of equipment and reduction of internal components.

Battery overcharge will be avoided by the usage of a premade battery charger with a built-in cell balancer. With this, the lithium polymer batteries can be safely charged and discharged as needed. In addition, to further minimize the risk of battery fires it is required that the batteries be always monitored while charging. If a fire does break out, the lithium polymer batteries will be stored in a premade fire and explosion proof container while charging and discharging.

While overall voltages within the design are limited to a maximum of 16.8 volts and as such are not a significant risk, a large volume of amperage will still be in use while the design is active. Because of this, it will be required that any user interacting with the internals of the design will be required to disconnect all power sources and wear appropriate electrical gloves.

Internal Heat

Due to the high volume of energy flow within this design, heat poses a potential risk to both the user and the vehicle itself. The basic design incorporates a water pump-based cooling system to protect the sensitive internal components. However, if cooling fails there is the chance that the internal metal components could become dangerously hot to the touch. It is recommended that users measure the temperature of the internals using a laser thermometer or equivalent tool. Additionally, it is recommended that user wear heat resistant gloves when working with high temperature components.

Pinching

The large number of gear interfaces, high torques, and high RPMs present in this design could lead to pinching for users. As stated under the electrical risks, it is required that all power sources be disconnected before working on the vehicle’s internals. This will doubly serve to minimize the risk of pinching in the design.

Muscle Strain

Since the final design weighed 90 pounds, it is not recommended that any user attempt to move the design individually. We suggest that a minimum of two users be present to pick up and reposition the vehicle as needed to reduce the risk of muscle strain. If multiple operators are not present, it is recommended the weight plates and electronics are removed before moving the body.

Time & Scheduling Constraints

Since this project is operating under stringent time constraints, we have adopted methods to track and divide work among group members using Microsoft Project. Further details can be found under **PROJECT PLAN**.

Budget Constraints

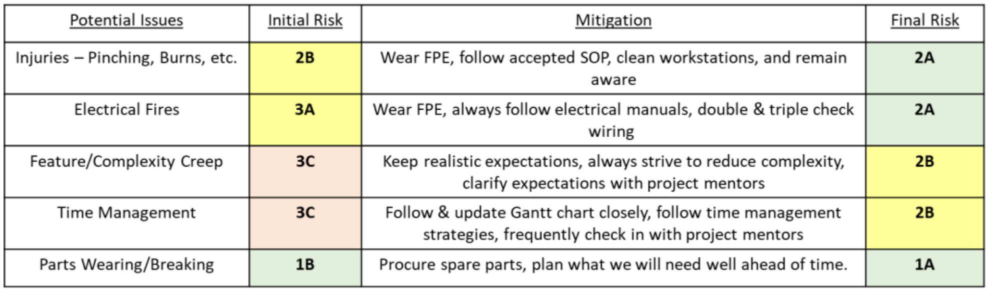
Due to the high cost of premade mechanical parts, our project could have gone over the allotted $4000 budget. Revisions to the design to procure the cheapest available parts has been a continuous aspect of this project. Steps have been taken to evaluate stresses within materials to use cheaper materials in all aspects of the design. In addition, multiple redesigns have taken place to reduce the required budget.

Multiple vendor sources have been considered to find the cheapest options for needed materials and parts.

Manufacturing and Assembly Errors

Since this project has exceeded the allotted budget, it is doubly important to ensure that a mistake in manufacturing and assembly will not cause further budget excesses. To mitigate this, we have engaged in multiple redesigns that will significantly reduce the difficulty of manufacturing, such as a switch from press fitted gears to a keyed shaft design. Throughout the design process we have maintained contact with available engineers and professors on advice for minimizing manufacturing risks.

Components that have the risk of breaking or tripping have been ordered in excess, such as the multiple fuses present within the design. Excess raw material will also be present to allow for minor errors within manufacturing.



Potential Issues	Initial Risk	Mitigation	Final Risk
Injuries – Pinching, Burns, etc.	**2B**	Wear FPE, follow accepted SOP, clean workstations, and remain aware	**2A**
Electrical Fires	**3A**	Wear FPE, always follow electrical manuals, double & triple check wiring	**2A**
Feature/Complexity Creep	**3C**	Keep realistic expectations, always strive to reduce complexity, clarify expectations with project mentors	**2B**
Time Management	**3C**	Follow & update Gantt chart closely, follow time management strategies, frequently check in with project mentors	**2B**
Parts Wearing/Breaking	**1B**	Procure spare parts, plan what we will need well ahead of time.	**1A**

Figure 57. Risk Mitigation Table

Risk	1 – Minor Severity	2 – Moderate Severity	3 – Significant Severity
A - Very Unlikely	**Low**	**Low**	**Med**
B - Likely	**Low**	**Med**	**High**
C - Very Likely	**Med**	**High**	**High**

Figure 58. Risk Matrix

Overall, the two environmental risks would be grease and electricity getting into the water. However, this is mitigated by the waterproof outer coating, waterproof bearings, and gaskets installed. Otherwise, the KRIMP is generally harmless to the environment.

Locomotion System

The locomotion system has the largest potential for risk in the whole project. Everything depends on the locomotion running smoothly, consistently, and effectively. If the locomotion system were to stall or the gears were to jam, the whole device would be at risk for damage.

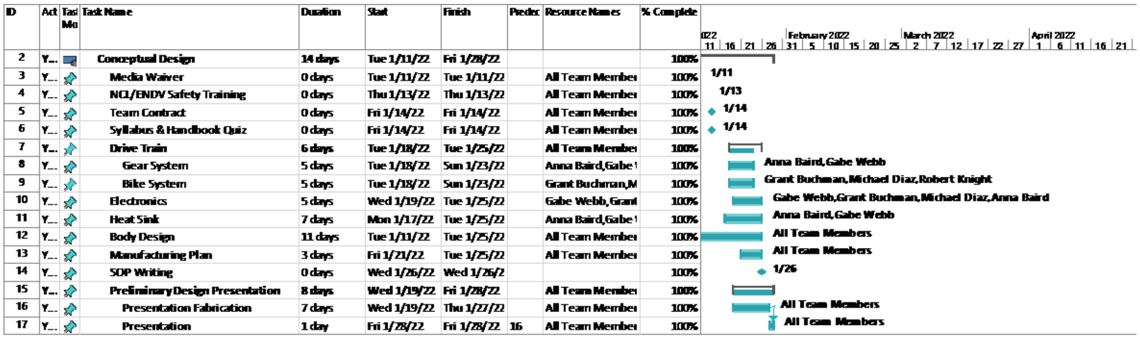
To ensure that the locomotion system was driven smoothly, we utilized marine grease to lubricate all gears so that the appropriate friction was present for proper meshing and function. Also, many tests were performed on each piece of the drive train throughout the fabrication process, as well as appropriate stress and torque analysis over each subsystem within the locomotion. During the individual testing phases, the locomotion was tested after each part of its manufacturing to ensure each part was appropriately secured and strong. We also tested the locomotion system functionality without and with the paddles attached at multiple different RPMs prior to placing inside the body to ensure the motion was correct and no issues would rise within the system. Once the locomotion system was placed within the body, we began testing it in air, at the slowest possible RPM, then gradually increased the given speed gradually.

This multi-stage testing of the locomotion system itself, along with proper analysis and lubrication, allowed our team to mitigate the risks of the locomotion system as much as possible.

PROJECT PLAN

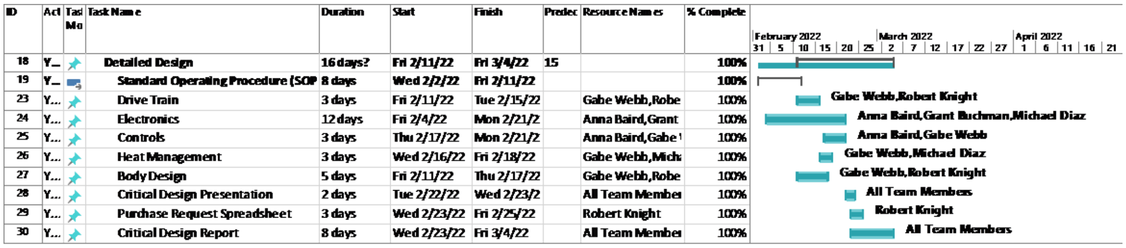
Throughout the project we had a very tight schedule based on the amount of work due. A Microsoft Project file was created to effectively track our progress and make sure we would complete our goals by the due date. To make organization even easier, we split up our entire project into five main Phases: Conceptual Design phase, Detailed Design phase, Fabrication Phase, Testing and Validation Phase, and Complete Documentation Phase. We referred to these phases simply as Phases 1 – 5. On the following page, it is possible to see the actual sections split up as seen in the project file.

Final Project Plan



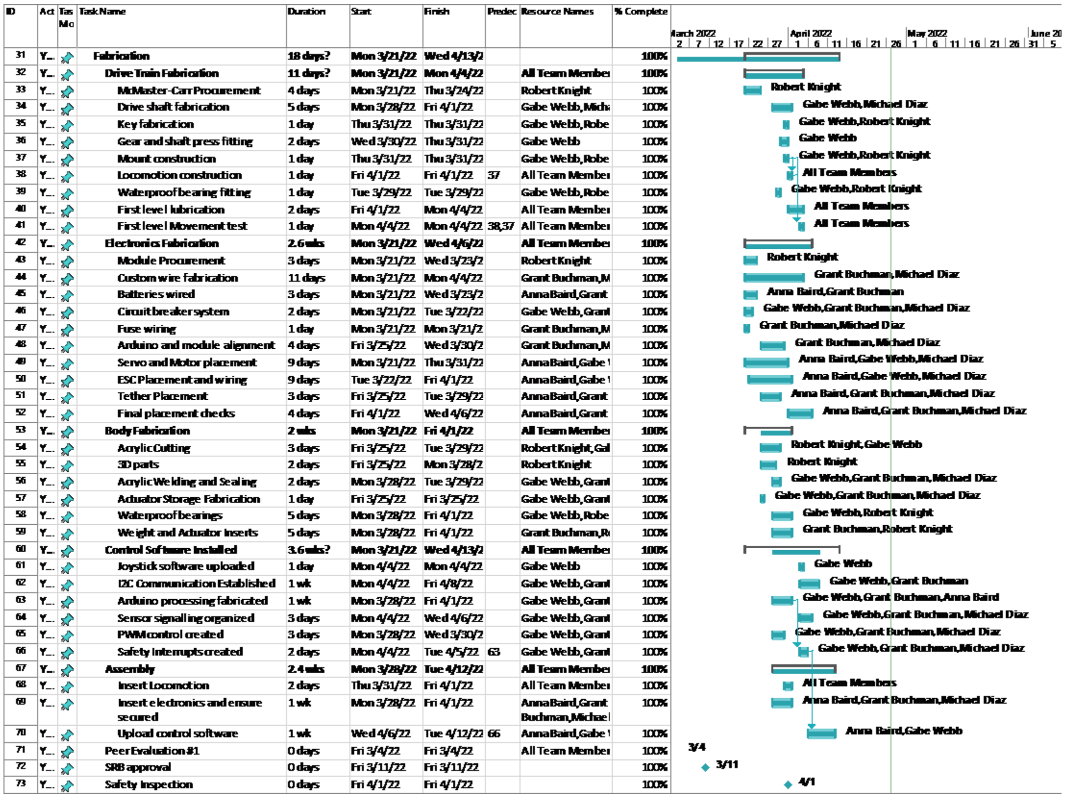
ID	Act	Tas Mo	Task Name	Duration	Start	Finish	Predec	Resource Names	% Complete
2	Y...		Conceptual Design	14 days	Tue 1/11/22	Fri 1/28/22			100%
3	Y...		Media Waiver	0 days	Tue 1/11/22	Tue 1/11/22		All Team Membe	100%
4	Y...		NCL/ENDV Safety Training	0 days	Thu 1/13/22	Thu 1/13/22		All Team Membe	100%
5	Y...		Team Contract	0 days	Fri 1/14/22	Fri 1/14/22		All Team Membe	100%
6	Y...		Syllabus & Handbook Quiz	0 days	Fri 1/14/22	Fri 1/14/22		All Team Membe	100%
7	Y...		Drive Train	6 days	Tue 1/18/22	Tue 1/25/22		All Team Membe	100%
8	Y...		Gear System	5 days	Tue 1/18/22	Sun 1/23/22		Anna Baird,Gabe	100%
9	Y...		Bike System	5 days	Tue 1/18/22	Sun 1/23/22		Grant Buchman,M	100%
10	Y...		Electronics	5 days	Wed 1/19/22	Tue 1/25/22		Gabe Webb,Grant	100%
11	Y...		Heat Sink	7 days	Mon 1/17/22	Tue 1/25/22		Anna Baird,Gabe	100%
12	Y...		Body Design	11 days	Tue 1/11/22	Tue 1/25/22		All Team Membe	100%
13	Y...		Manufacturing Plan	3 days	Fri 1/21/22	Tue 1/25/22		All Team Membe	100%
14	Y...		SOP Writing	0 days	Wed 1/26/22	Wed 1/26/2			100%
15	Y...		Preliminary Design Presentation	8 days	Wed 1/19/22	Fri 1/28/22		All Team Membe	100%
16	Y...		Presentation Fabrication	7 days	Wed 1/19/22	Thu 1/27/22		All Team Membe	100%
17	Y...		Presentation	1 day	Fri 1/28/22	Fri 1/28/22	16	All Team Membe	100%

Figure 59. Phase 1 - Conceptual Design



ID	Act	Tas Mo	Task Name	Duration	Start	Finish	Predec	Resource Names	% Complete
18	Y...		Detailed Design	16 days?	Fri 2/11/22	Fri 3/4/22	15		100%
19	Y...		Standard Operating Procedure (SOP	8 days	Wed 2/2/22	Fri 2/11/22			100%
23	Y...		Drive Train	3 days	Fri 2/11/22	Tue 2/15/22		Gabe Webb,Robe	100%
24	Y...		Electronics	12 days	Fri 2/4/22	Mon 2/21/2		Anna Baird,Grant	100%
25	Y...		Controls	3 days	Thu 2/17/22	Mon 2/21/2		Anna Baird,Gabe	100%
26	Y...		Heat Management	3 days	Wed 2/16/22	Fri 2/18/22		Gabe Webb,Mich	100%
27	Y...		Body Design	5 days	Fri 2/11/22	Thu 2/17/22		Gabe Webb,Robe	100%
28	Y...		Critical Design Presentation	2 days	Tue 2/22/22	Wed 2/23/2		All Team Membe	100%
29	Y...		Purchase Request Spreadsheet	3 days	Wed 2/23/22	Fri 2/25/22		Robert Knight	100%
30	Y...		Critical Design Report	8 days	Wed 2/23/22	Fri 3/4/22		All Team Membe	100%

Figure 60. Phase 2 - Detailed Design



ID	Act	Tas Mo	Task Name	Duration	Start	Finish	Predec	Resource Names	% Complete
31	Y...		Fabrication	18 days?	Mon 3/21/22	Wed 4/13/2			100%
32	Y...		Drive Train Fabrication	11 days?	Mon 3/21/22	Mon 4/4/22		All Team Membe	100%
33	Y...		McMaster-Carr Procurement	4 days	Mon 3/21/22	Thu 3/24/22		Robert Knight	100%
34	Y...		Drive shaft fabrication	5 days	Mon 3/28/22	Fri 4/1/22		Gabe Webb,Mich	100%
35	Y...		Key fabrication	1 day	Thu 3/31/22	Thu 3/31/22		Gabe Webb,Robe	100%
36	Y...		Gear and shaft press fitting	2 days	Wed 3/30/22	Thu 3/31/22		Gabe Webb	100%
37	Y...		Mount construction	1 day	Thu 3/31/22	Thu 3/31/22		Gabe Webb,Robe	100%
38	Y...		Locomotion construction	1 day	Fri 4/1/22	Fri 4/1/22	37	All Team Membe	100%
39	Y...		Waterproof bearing fitting	1 day	Tue 3/29/22	Tue 3/29/22		Gabe Webb,Robe	100%
40	Y...		First level lubrication	2 days	Fri 4/1/22	Mon 4/4/22		All Team Membe	100%
41	Y...		First level Movement test	1 day	Mon 4/4/22	Mon 4/4/22	38,37	All Team Membe	100%
42	Y...		Electronics Fabrication	2.6 wks	Mon 3/21/22	Wed 4/6/22		All Team Membe	100%
43	Y...		Module Procurement	3 days	Mon 3/21/22	Wed 3/23/2		Robert Knight	100%
44	Y...		Custom wire fabrication	11 days	Mon 3/21/22	Mon 4/4/22		Grant Buchman,M	100%
45	Y...		Batteries wired	3 days	Mon 3/21/22	Wed 3/23/2		Anna Baird,Grant	100%
46	Y...		Circuit breaker system	2 days	Mon 3/21/22	Tue 3/22/22		Gabe Webb,Grant	100%
47	Y...		Fuse wiring	1 day	Mon 3/21/22	Mon 3/21/2		Grant Buchman,M	100%
48	Y...		Arduino and module alignment	4 days	Fri 3/25/22	Wed 3/30/2		Grant Buchman,M	100%
49	Y...		Servo and Motor placement	9 days	Mon 3/21/22	Thu 3/31/22		Anna Baird,Gabe	100%
50	Y...		ESC Placement and wiring	9 days	Tue 3/22/22	Fri 4/1/22		Anna Baird,Gabe	100%
51	Y...		Tether Placement	3 days	Fri 3/25/22	Tue 3/29/22		Anna Baird,Grant	100%
52	Y...		Final placement checks	4 days	Fri 4/1/22	Wed 4/6/22		Anna Baird,Grant	100%
53	Y...		Body Fabrication	2 wks	Mon 3/21/22	Fri 4/1/22		All Team Membe	100%
54	Y...		Acrylic Cutting	3 days	Fri 3/25/22	Tue 3/29/22		Robert Knight,Gal	100%
55	Y...		3D parts	2 days	Fri 3/25/22	Mon 3/28/2		Robert Knight	100%
56	Y...		Acrylic Welding and Sealing	2 days	Mon 3/28/22	Tue 3/29/22		Gabe Webb,Grant	100%
57	Y...		Actuator Storage Fabrication	1 day	Fri 3/25/22	Fri 3/25/22		Gabe Webb,Grant	100%
58	Y...		Waterproof bearings	5 days	Mon 3/28/22	Fri 4/1/22		Gabe Webb,Robe	100%
59	Y...		Weight and Actuator Inserts	5 days	Mon 3/28/22	Fri 4/1/22		Grant Buchman,R	100%
60	Y...		Control Software Installed	3.6 wks?	Mon 3/21/22	Wed 4/13/2		All Team Membe	100%
61	Y...		Joystick software uploaded	1 day	Mon 4/4/22	Mon 4/4/22		Gabe Webb	100%
62	Y...		I2C Communication Established	1 wk	Mon 4/4/22	Fri 4/8/22		Gabe Webb,Grant	100%
63	Y...		Arduino processing fabricated	1 wk	Mon 3/28/22	Fri 4/1/22		Gabe Webb,Grant	100%
64	Y...		Sensor signalling organized	3 days	Mon 4/4/22	Wed 4/6/22		Gabe Webb,Grant	100%
65	Y...		PWM control created	3 days	Mon 3/28/22	Wed 3/30/2		Gabe Webb,Grant	100%
66	Y...		Safety Interrupts created	2 days	Mon 4/4/22	Tue 4/5/22	63	Gabe Webb,Grant	100%
67	Y...		Assembly	2.4 wks	Mon 3/28/22	Tue 4/12/22		All Team Membe	100%
68	Y...		Insert Locomotion	2 days	Thu 3/31/22	Fri 4/1/22		All Team Membe	100%
69	Y...		Insert electronics and ensure secured	1 wk	Mon 3/28/22	Fri 4/1/22		Anna Baird,Grant Buchman,Michael	100%
70	Y...		Upload control software	1 wk	Wed 4/6/22	Tue 4/12/22	66	Anna Baird,Gabe	100%
71	Y...		Peer Evaluation #1	0 days	Fri 3/4/22	Fri 3/4/22		All Team Membe	100%
72	Y...		SRB approval	0 days	Fri 3/11/22	Fri 3/11/22			100%
73	Y...		Safety Inspection	0 days	Fri 4/1/22	Fri 4/1/22			100%

Figure 61. Phase 3 - Fabrication

ID	Act	Tas Mo	Task Name	Duration	Start	Finish	Predec	Resource Names	% Complete
74	Y...		**Testing and Validation**	**9 days?**	**Tue 4/12/22**	**Fri 4/22/22**	**73**		**100%**
75	Y...		**Heat Analysis**	**9 days?**	**Tue 4/12/22**	**Fri 4/22/22**		**Anna Baird,Gabe**	**100%**
76	Y...		Motor Test (w/ Dr. Bai)	3 days	Tue 4/12/22	Thu 4/14/22			100%
77	Y...		Electronics Observation	3 days	Wed 4/13/22	Fri 4/15/22			100%
78	Y...		Heat Strain Test	2 days	Fri 4/15/22	Mon 4/18/2			100%
79	Y...		**Control System Test**	**9 days?**	**Tue 4/12/22**	**Fri 4/22/22**		**Anna Baird,Gabe**	**100%**
80	Y...		Servo movement	1 day	Mon 4/18/22	Mon 4/18/2			100%
81	Y...		Motor PWM validation	2 days	Mon 4/18/22	Tue 4/19/22			100%
82	Y...		Sensor Accuracy	3 days	Tue 4/19/22	Thu 4/21/22			100%
83	Y...		**Drive Train Test**	**9 days?**	**Tue 4/12/22**	**Fri 4/22/22**		**All Team Membe**	**100%**
84	Y...		Stress Test	2 days	Tue 4/12/22	Wed 4/13/2			100%
85	Y...		Speed Test	2 days	Tue 4/12/22	Wed 4/13/2			100%
86	Y...		Torque Test	2 days	Tue 4/12/22	Wed 4/13/2			100%
87	Y...		Lubrication Efficiency	1 day	Wed 4/13/22	Wed 4/13/2			100%
88	Y...		Waterproof Efficacy	3 days	Thu 4/14/22	Mon 4/18/2			100%
89	Y...		Movement in Water	5 days	Mon 4/18/22	Fri 4/22/22			100%
90	Y...		Project Video	0 days	Tue 4/12/22	Tue 4/12/22		All Team Membe	100%
91	Y...		Final Presentation and EXPO	0 days	Fri 4/22/22	Fri 4/22/22		All Team Membe	100%

Figure 62. Phase 4 - Testing and Validation

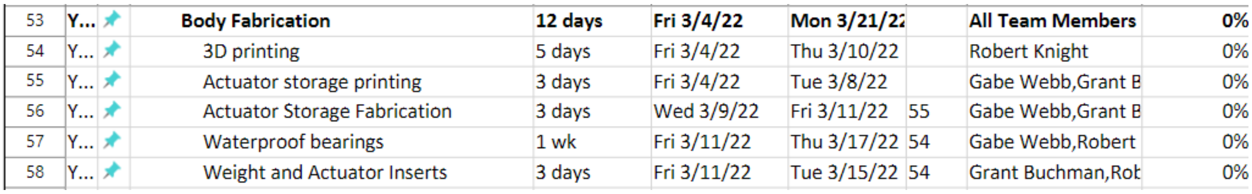
ID	Act	Tas Mo	Task Name	Duration	Start	Finish	Predec	Resource Names	% Complete
92	Y...		**Complete Documentation**	**5 days**	**Fri 4/29/22**	**Fri 5/6/22**	**91**		**0%**
93	Y...		Final Report	0 days	Fri 4/29/22	Fri 4/29/22		All Team Membe	0%
94	Y...		Peer Evaluation #2	0 days	Fri 4/29/22	Fri 4/29/22		All Team Membe	100%
95	Y...		Final Exam	0 days	Thu 5/5/22	Thu 5/5/22		All Team Membe	0%
96	Y...		All Filed Submitted	0 days	Fri 5/6/22	Fri 5/6/22		All Team Membe	0%

Figure 63. Phase 5 - Complete Documentation

The five phases of this design process taught our team a lot. We were right on schedule through the conceptual design phase and the detailed design phase. However, after our Critical Design Presentation, we lacked the proper analysis to continue forward with the fabrication phase. This set us back from ordering all the necessary parts for approximately a week. This then added delays and challenges on getting everything shipped in a timely manner so that fabrication could begin. The fabrication phase took approximately two weeks and required a lot of time and effort from all team members. Due to the high number of parts, a lot of extra time was put into this phase than initially planned for. Due to this factor, the testing phase was limited to only about a week, rather than the two weeks originally planned for. Luckily, despite all the setbacks and challenges, our team was able to create a successful, working prototype that performed and swam at Expo.

Project Plan Changes and Revisions

Although the current plan shown above (Figure -Figure) seem well organized and designed, there have been several changes since the start of the project. At the start of the project, we were docked points for not having enough detail in our Microsoft Project. Due to this, Michael Diaz, the Team Planner, and master of the MS Project, revised the entire table to make it much more specific. After this, the most noticeable changes were made to the body, communication system, and controls sections (Figure & **Error! Reference source not found.**).



53	Y...		**Body Fabrication**	**12 days**	**Fri 3/4/22**	**Mon 3/21/2**		**All Team Members**	**0%**
54	Y...		3D printing	5 days	Fri 3/4/22	Thu 3/10/22		Robert Knight	0%
55	Y...		Actuator storage printing	3 days	Fri 3/4/22	Tue 3/8/22		Gabe Webb,Grant B	0%
56	Y...		Actuator Storage Fabrication	3 days	Wed 3/9/22	Fri 3/11/22	55	Gabe Webb,Grant B	0%
57	Y...		Waterproof bearings	1 wk	Fri 3/11/22	Thu 3/17/22	54	Gabe Webb,Robert	0%
58	Y...		Weight and Actuator Inserts	3 days	Fri 3/11/22	Tue 3/15/22	54	Grant Buchman,Rob	0%

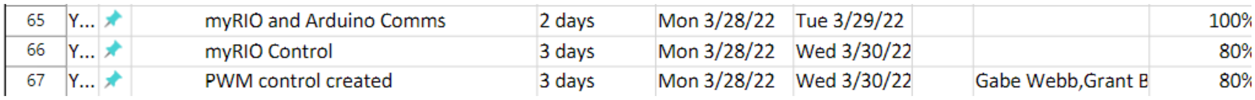
Figure 64. The original plan for the 3D body

59	**Y...**	📌	**Control Software Installed**	**3.4 wks**	**Fri 3/11/22**	**Mon 4/4/22**	**42**	**All Team Members**	**0%**
60	Y...	📌	Joystick software uploaded	5 days	Fri 3/11/22	Thu 3/17/22		Gabe Webb	0%
61	Y...	📌	CAN Packet sending established	2 wks	Mon 3/14/22	Fri 3/25/22		Gabe Webb,Grant B	0%
62	Y...	📌	Arduino processing fabricated	2 wks	Mon 3/14/22	Fri 3/25/22		Gabe Webb,Grant B	0%
63	Y...	📌	Sensor signalling organized	2 wks	Thu 3/17/22	Wed 3/30/22		Gabe Webb,Grant B	0%
64	Y...	📌	PWM control created	2 wks	Fri 3/18/22	Thu 3/31/22		Gabe Webb,Grant B	0%
65	Y...	📌	Safety Interrupts created	2 wks	Tue 3/22/22	Mon 4/4/22		Gabe Webb,Grant B	0%

Figure 65: Original Software communication and controls

After the 3D printer broke, our group quickly rotated to using acrylic sheets instead thus changing Figure , into the body fabrication seen in Figure . As for the control software, most parts stayed the same, however the use of CAN was abandoned in the final design due to time constraints, and creeping complexity of using CAN-bus.

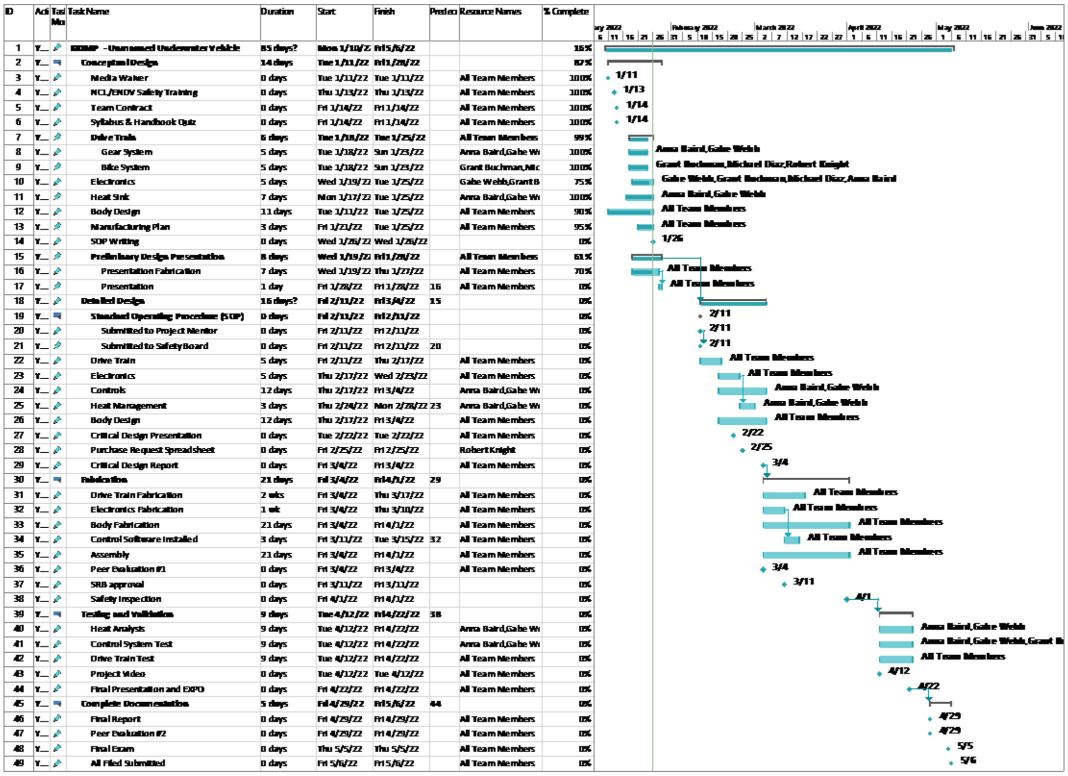
In week 11, we had another problem. We were unable to get the NEO Brushless Motors to work correctly via Arduino. However, we were able to run them from a myRIO we had access to. This was reflected in that week's project (Figure).



65	Y...	📌	myRIO and Arduino Comms	2 days	Mon 3/28/22	Tue 3/29/22			100%
66	Y...	📌	myRIO Control	3 days	Mon 3/28/22	Wed 3/30/22			80%
67	Y...	📌	PWM control created	3 days	Mon 3/28/22	Wed 3/30/22		Gabe Webb,Grant B	80%

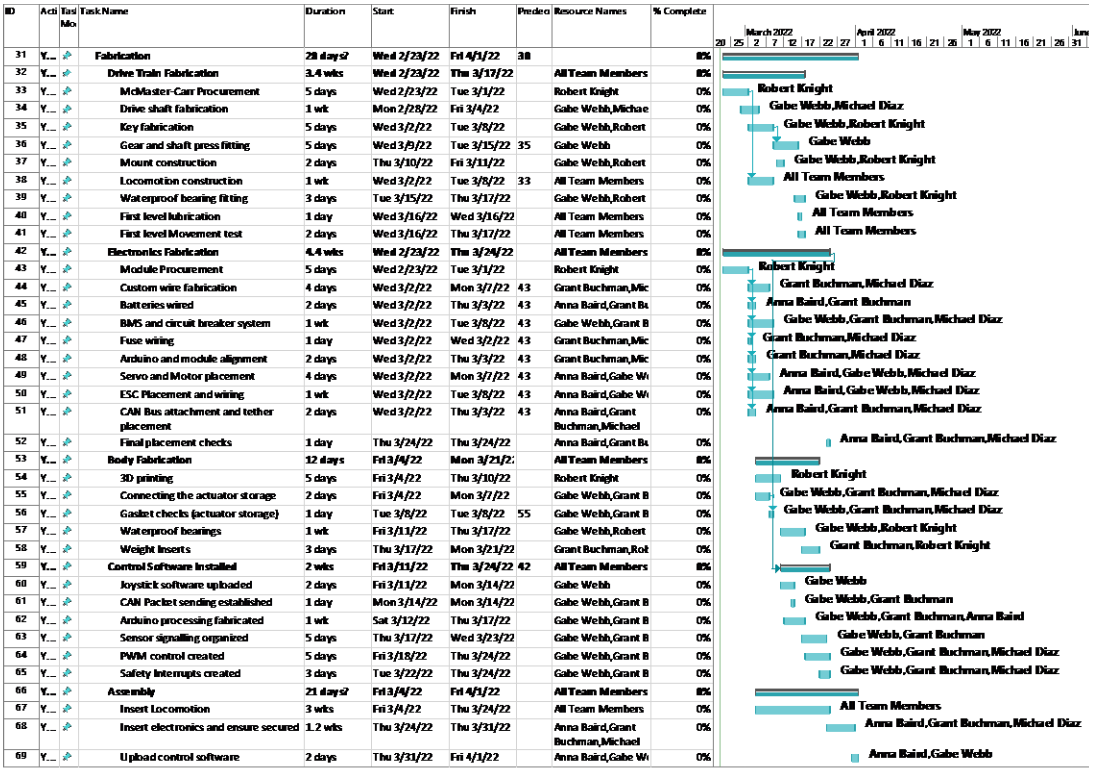
Figure 66. myRIO added to the control software fabrication phase

Thankfully, we were able to figure out the original problem with the Arduino, and subsequently removed the myRIO from the plan, greatly simplifying not only coding, but also space management. The only other changes were date changes, and those are far too numerous to be able to cover in an effective way. It should simply be stated that the largest amount of time variation was after the CDR was rejected and had to be presented again twice.



ID	Acti	Tas Mo	Task Name	Duration	Start	Finish	Predeo	Resource Names	% Complete
1	Y...		**ROMP - Unmanned Underwater Vehicle**	**85 days?**	**Mon 1/10/2**	**Fri 5/6/22**			**16%**
2	Y...		**Conceptual Design**	**14 days**	**Tue 1/11/22**	**Fri 1/28/22**			**87%**
3	Y...		Media Waiver	0 days	Tue 1/11/22	Tue 1/11/22		All Team Members	100%
4	Y...		NCL/ENDV Safety Training	0 days	Thu 1/13/22	Thu 1/13/22		All Team Members	100%
5	Y...		Team Contract	0 days	Fri 1/14/22	Fri 1/14/22		All Team Members	100%
6	Y...		Syllabus & Handbook Quiz	0 days	Fri 1/14/22	Fri 1/14/22		All Team Members	100%
7	Y...		**Drive Train**	**6 days**	**Tue 1/18/22**	**Tue 1/25/22**		**All Team Members**	**99%**
8	Y...		Gear System	5 days	Tue 1/18/22	Sun 1/23/22		Anna Baird,Gabe W	100%
9	Y...		Bike System	5 days	Tue 1/18/22	Sun 1/23/22		Grant Buchman,Mic	100%
10	Y...		Electronics	5 days	Wed 1/19/22	Tue 1/25/22		Gabe Webb,Grant B	75%
11	Y...		Heat Sink	7 days	Mon 1/17/22	Tue 1/25/22		Anna Baird,Gabe W	100%
12	Y...		Body Design	11 days	Tue 1/11/22	Tue 1/25/22		All Team Members	90%
13	Y...		Manufacturing Plan	3 days	Fri 1/21/22	Tue 1/25/22		All Team Members	95%
14	Y...		SOP Writing	0 days	Wed 1/26/22	Wed 1/26/22			0%
15	Y...		**Preliminary Design Presentation**	**8 days**	**Wed 1/19/22**	**Fri 1/28/22**		**All Team Members**	**61%**
16	Y...		Presentation Fabrication	7 days	Wed 1/19/22	Thu 1/27/22		All Team Members	70%
17	Y...		Presentation	1 day	Fri 1/28/22	Fri 1/28/22	16	All Team Members	0%
18	Y...		**Detailed Design**	**16 days?**	**Fri 2/11/22**	**Fri 3/4/22**	15		**0%**
19	Y...		**Standard Operating Procedure (SOP)**	**0 days**	**Fri 2/11/22**	**Fri 2/11/22**			**0%**
20	Y...		Submitted to Project Mentor	0 days	Fri 2/11/22	Fri 2/11/22			0%
21	Y...		Submitted to Safety Board	0 days	Fri 2/11/22	Fri 2/11/22	20		0%
22	Y...		Drive Train	5 days	Fri 2/11/22	Thu 2/17/22		All Team Members	0%
23	Y...		Electronics	5 days	Thu 2/17/22	Wed 2/23/22		All Team Members	0%
24	Y...		Controls	12 days	Thu 2/17/22	Fri 3/4/22		Anna Baird,Gabe W	0%
25	Y...		Heat Management	3 days	Thu 2/24/22	Mon 2/28/22	23	Anna Baird,Gabe W	0%
26	Y...		Body Design	12 days	Thu 2/17/22	Fri 3/4/22		All Team Members	0%
27	Y...		Critical Design Presentation	0 days	Tue 2/22/22	Tue 2/22/22		All Team Members	0%
28	Y...		Purchase Request Spreadsheet	0 days	Fri 2/25/22	Fri 2/25/22		Robert Knight	0%
29	Y...		Critical Design Report	0 days	Fri 3/4/22	Fri 3/4/22		All Team Members	0%
30	Y...		**Fabrication**	**21 days**	**Fri 3/4/22**	**Fri 4/1/22**	29		**0%**
31	Y...		Drive Train Fabrication	2 wks	Fri 3/4/22	Thu 3/17/22		All Team Members	0%
32	Y...		Electronics Fabrication	1 wk	Fri 3/4/22	Thu 3/10/22		All Team Members	0%
33	Y...		Body Fabrication	21 days	Fri 3/4/22	Fri 4/1/22		All Team Members	0%
34	Y...		Control Software Installed	3 days	Fri 3/11/22	Tue 3/15/22	32	All Team Members	0%
35	Y...		Assembly	21 days	Fri 3/4/22	Fri 4/1/22		All Team Members	0%
36	Y...		Peer Evaluation #1	0 days	Fri 3/4/22	Fri 3/4/22		All Team Members	0%
37	Y...		SRB approval	0 days	Fri 3/11/22	Fri 3/11/22			0%
38	Y...		Safety Inspection	0 days	Fri 4/1/22	Fri 4/1/22			0%
39	Y...		**Testing and Validation**	**9 days**	**Tue 4/12/22**	**Fri 4/22/22**	38		**0%**
40	Y...		Heat Analysis	9 days	Tue 4/12/22	Fri 4/22/22		Anna Baird,Gabe W	0%
41	Y...		Control System Test	9 days	Tue 4/12/22	Fri 4/22/22		Anna Baird,Gabe W	0%
42	Y...		Drive Train Test	9 days	Tue 4/12/22	Fri 4/22/22		All Team Members	0%
43	Y...		Project Video	0 days	Tue 4/12/22	Tue 4/12/22		All Team Members	0%
44	Y...		Final Presentation and EXPO	0 days	Fri 4/22/22	Fri 4/22/22		All Team Members	0%
45	Y...		**Complete Documentation**	**5 days**	**Fri 4/29/22**	**Fri 5/6/22**	44		**0%**
46	Y...		Final Report	0 days	Fri 4/29/22	Fri 4/29/22		All Team Members	0%
47	Y...		Peer Evaluation #2	0 days	Fri 4/29/22	Fri 4/29/22		All Team Members	0%
48	Y...		Final Exam	0 days	Thu 5/5/22	Thu 5/5/22		All Team Members	0%
49	Y...		All Filed Submitted	0 days	Fri 5/6/22	Fri 5/6/22		All Team Members	0%

Figure 67. PDR Project



ID	Acti	Tas Mo	Task Name	Duration	Start	Finish	Predeo	Resource Names	% Complete
31	Y...		**Fabrication**	**28 days?**	**Wed 2/23/22**	**Fri 4/1/22**	**38**		**0%**
32	Y...		**Drive Train Fabrication**	**3.4 wks**	**Wed 2/23/22**	**Thu 3/17/22**		**All Team Members**	**0%**
33	Y...		McMaster-Carr Procurement	5 days	Wed 2/23/22	Tue 3/1/22		Robert Knight	0%
34	Y...		Drive shaft fabrication	1 wk	Mon 2/28/22	Fri 3/4/22		Gabe Webb,Michae	0%
35	Y...		Key fabrication	5 days	Wed 3/2/22	Tue 3/8/22		Gabe Webb,Robert	0%
36	Y...		Gear and shaft press fitting	5 days	Wed 3/9/22	Tue 3/15/22	35	Gabe Webb	0%
37	Y...		Mount construction	2 days	Thu 3/10/22	Fri 3/11/22		Gabe Webb,Robert	0%
38	Y...		Locomotion construction	1 wk	Wed 3/2/22	Tue 3/8/22	33	All Team Members	0%
39	Y...		Waterproof bearing fitting	3 days	Tue 3/15/22	Thu 3/17/22		Gabe Webb,Robert	0%
40	Y...		First level lubrication	1 day	Wed 3/16/22	Wed 3/16/22		All Team Members	0%
41	Y...		First level Movement test	2 days	Wed 3/16/22	Thu 3/17/22		All Team Members	0%
42	Y...		**Electronics Fabrication**	**4.4 wks**	**Wed 2/23/22**	**Thu 3/24/22**		**All Team Members**	**0%**
43	Y...		Module Procurement	5 days	Wed 2/23/22	Tue 3/1/22		Robert Knight	0%
44	Y...		Custom wire fabrication	4 days	Wed 3/2/22	Mon 3/7/22	43	Grant Buchman,Mic	0%
45	Y...		Batteries wired	2 days	Wed 3/2/22	Thu 3/3/22	43	Anna Baird,Grant Bu	0%
46	Y...		BMS and circuit breaker system	1 wk	Wed 3/2/22	Tue 3/8/22	43	Gabe Webb,Grant B	0%
47	Y...		Fuse wiring	1 day	Wed 3/2/22	Wed 3/2/22	43	Grant Buchman,Mic	0%
48	Y...		Arduino and module alignment	2 days	Wed 3/2/22	Thu 3/3/22	43	Grant Buchman,Mic	0%
49	Y...		Servo and Motor placement	4 days	Wed 3/2/22	Mon 3/7/22	43	Anna Baird,Gabe W	0%
50	Y...		ESC Placement and wiring	1 wk	Wed 3/2/22	Tue 3/8/22	43	Anna Baird,Gabe W	0%
51	Y...		CAN Bus attachment and tether placement	2 days	Wed 3/2/22	Thu 3/3/22	43	Anna Baird,Grant Buchman,Michael	0%
52	Y...		Final placement checks	1 day	Thu 3/24/22	Thu 3/24/22		Anna Baird,Grant Bu	0%
53	Y...		**Body Fabrication**	**12 days**	**Fri 3/4/22**	**Mon 3/21/2**		**All Team Members**	**0%**
54	Y...		3D printing	5 days	Fri 3/4/22	Thu 3/10/22		Robert Knight	0%
55	Y...		Connecting the actuator storage	2 days	Fri 3/4/22	Mon 3/7/22		Gabe Webb,Grant B	0%
56	Y...		Gasket checks (actuator storage)	1 day	Tue 3/8/22	Tue 3/8/22	55	Gabe Webb,Grant B	0%
57	Y...		Waterproof bearings	1 wk	Fri 3/11/22	Thu 3/17/22		Gabe Webb,Robert	0%
58	Y...		Weight Inserts	3 days	Thu 3/17/22	Mon 3/21/22		Grant Buchman,Rol	0%
59	Y...		**Control Software Installed**	**2 wks**	**Fri 3/11/22**	**Thu 3/24/22**	42	**All Team Members**	**0%**
60	Y...		Joystick software uploaded	2 days	Fri 3/11/22	Mon 3/14/22		Gabe Webb	0%
61	Y...		CAN Packet sending established	1 day	Mon 3/14/22	Mon 3/14/22		Gabe Webb,Grant B	0%
62	Y...		Arduino processing fabricated	1 wk	Sat 3/12/22	Thu 3/17/22		Gabe Webb,Grant B	0%
63	Y...		Sensor signalling organized	5 days	Thu 3/17/22	Wed 3/23/22		Gabe Webb,Grant B	0%
64	Y...		PWM control created	5 days	Fri 3/18/22	Thu 3/24/22		Gabe Webb,Grant B	0%
65	Y...		Safety Interrupts created	3 days	Tue 3/22/22	Thu 3/24/22		Gabe Webb,Grant B	0%
66	Y...		**Assembly**	**21 days?**	**Fri 3/4/22**	**Fri 4/1/22**		**All Team Members**	**0%**
67	Y...		Insert Locomotion	3 wks	Fri 3/4/22	Thu 3/24/22		All Team Members	0%
68	Y...		Insert electronics and ensure secured	1.2 wks	Thu 3/24/22	Thu 3/31/22		Anna Baird,Grant Buchman,Michael	0%
69	Y...		Upload control software	2 days	Thu 3/31/22	Fri 4/1/22		Anna Baird,Gabe W	0%

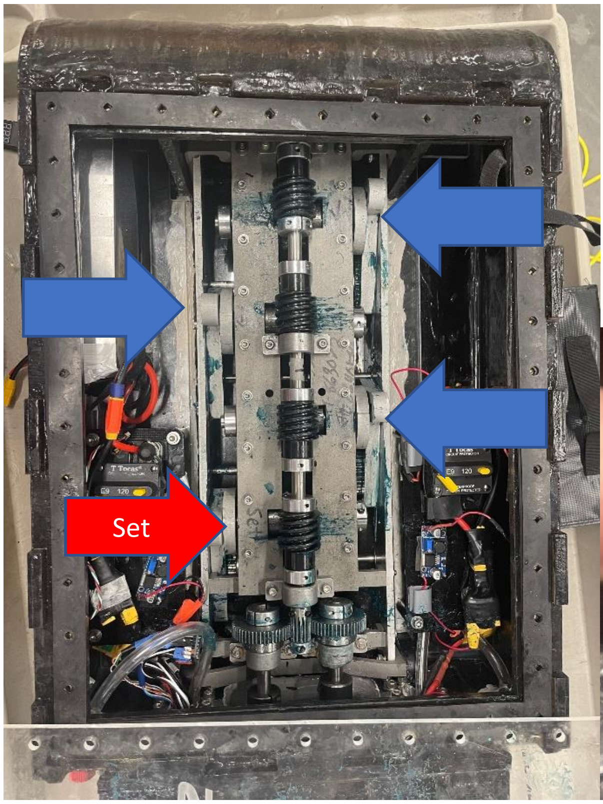
Figure 68. CDR Project

The main lessons we learned were to expect change and have enough time to deal with such change. It is also advisable to always have a contingency. If we had not had acrylic as a backup plan, there is a good chance we could have wasted several days figuring out a new solution. However, after the first print failure, Gabe made the acrylic plan as a backup and therefore we were able to rapidly shift to it once the 3D printer broke. In general, prepare for the worst and get on top of any changes as soon as you can.

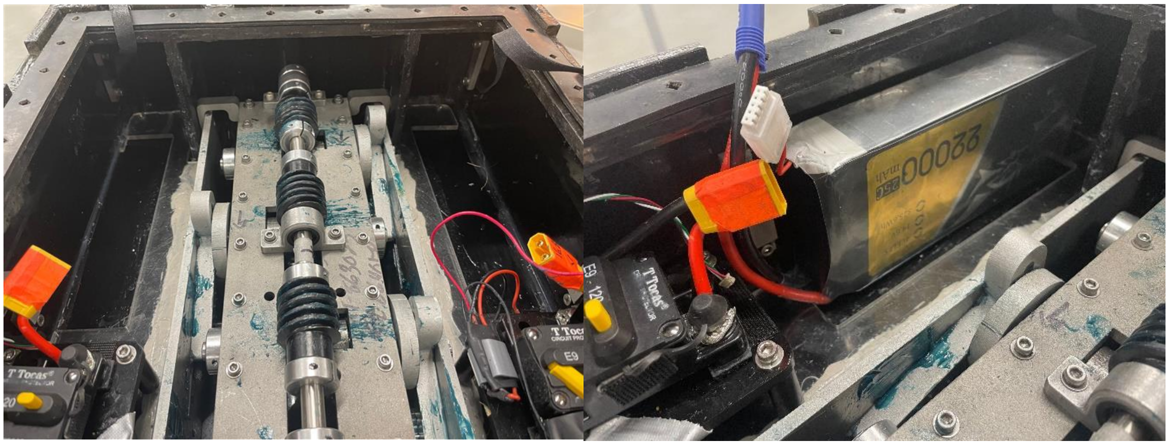
END-USER MANUAL

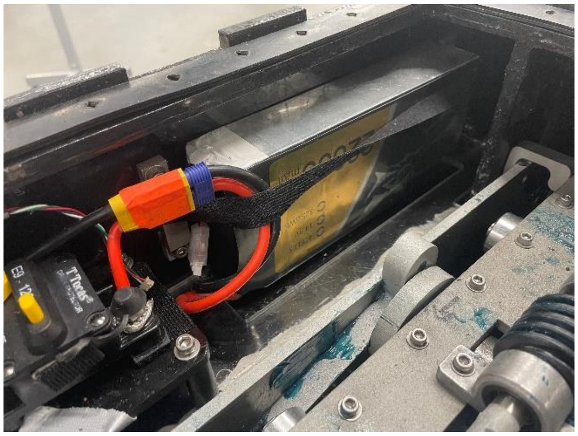
System Setup

1: Adjust phase lag between gears by rotating the outer hubs like shown in the figure. Use visual ques to reach desired amount:

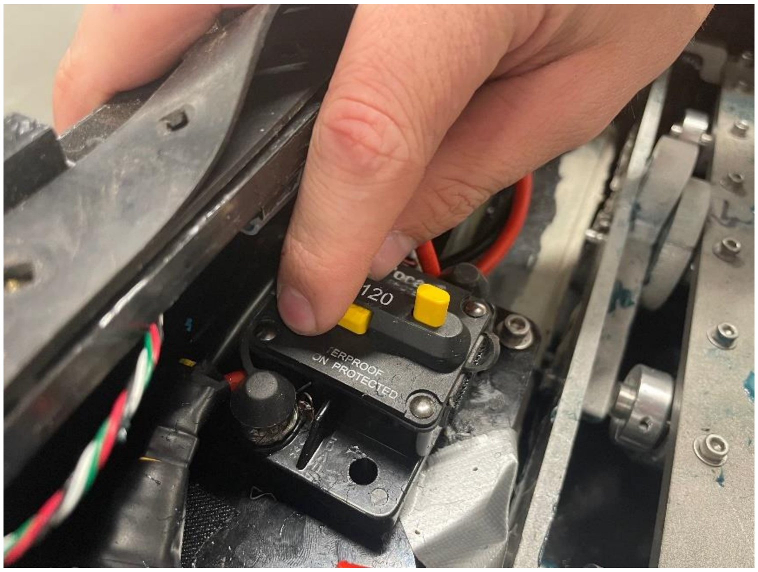


2: Install batteries inside the body. Once in place secure the battery and associated cables with the Velcro strap:

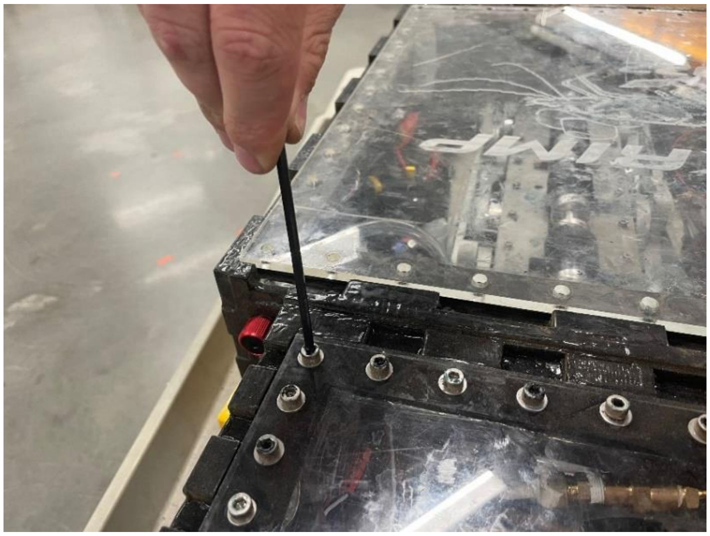




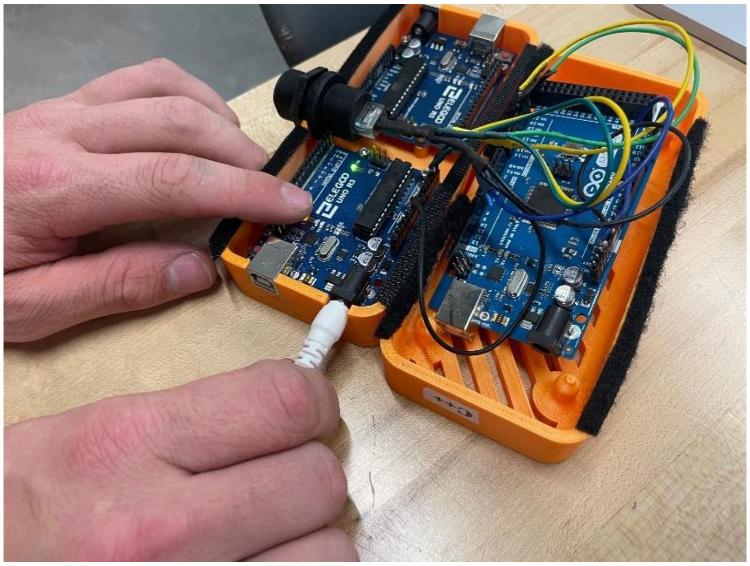
3: Flip the circuit breaker to power on the system:



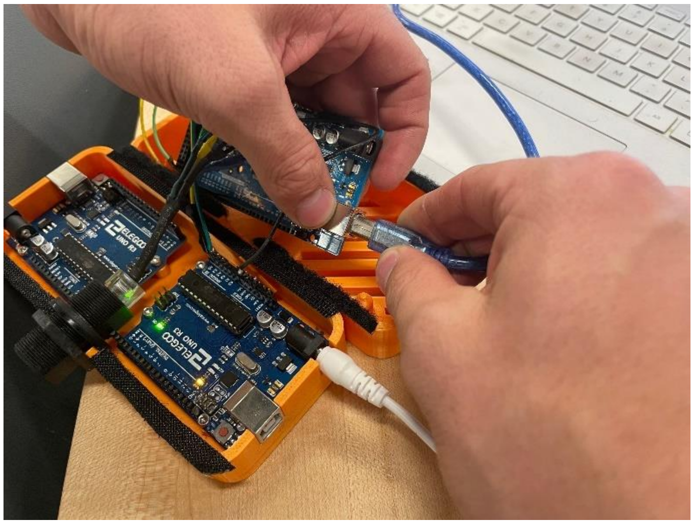
4: Screw Bolts into lid:



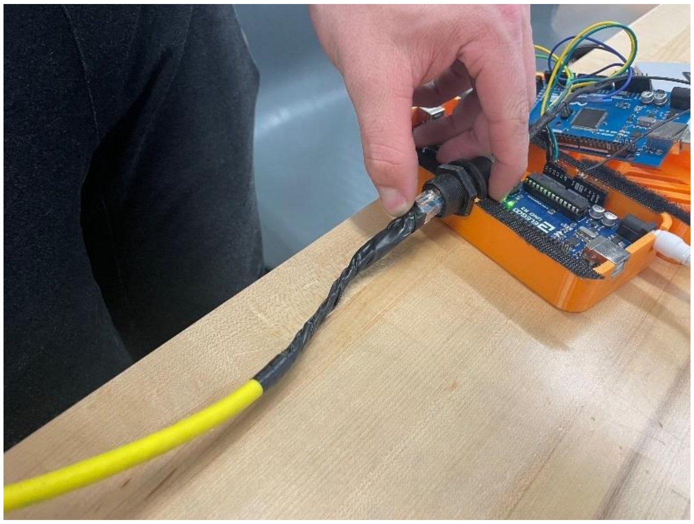
5: Plug power cable into C++ side of surface computer box:



6: Plug tether into surface computer box:



7: Plug tether into surface computer box:



8: Open LabVIEW GUI and begin operation:

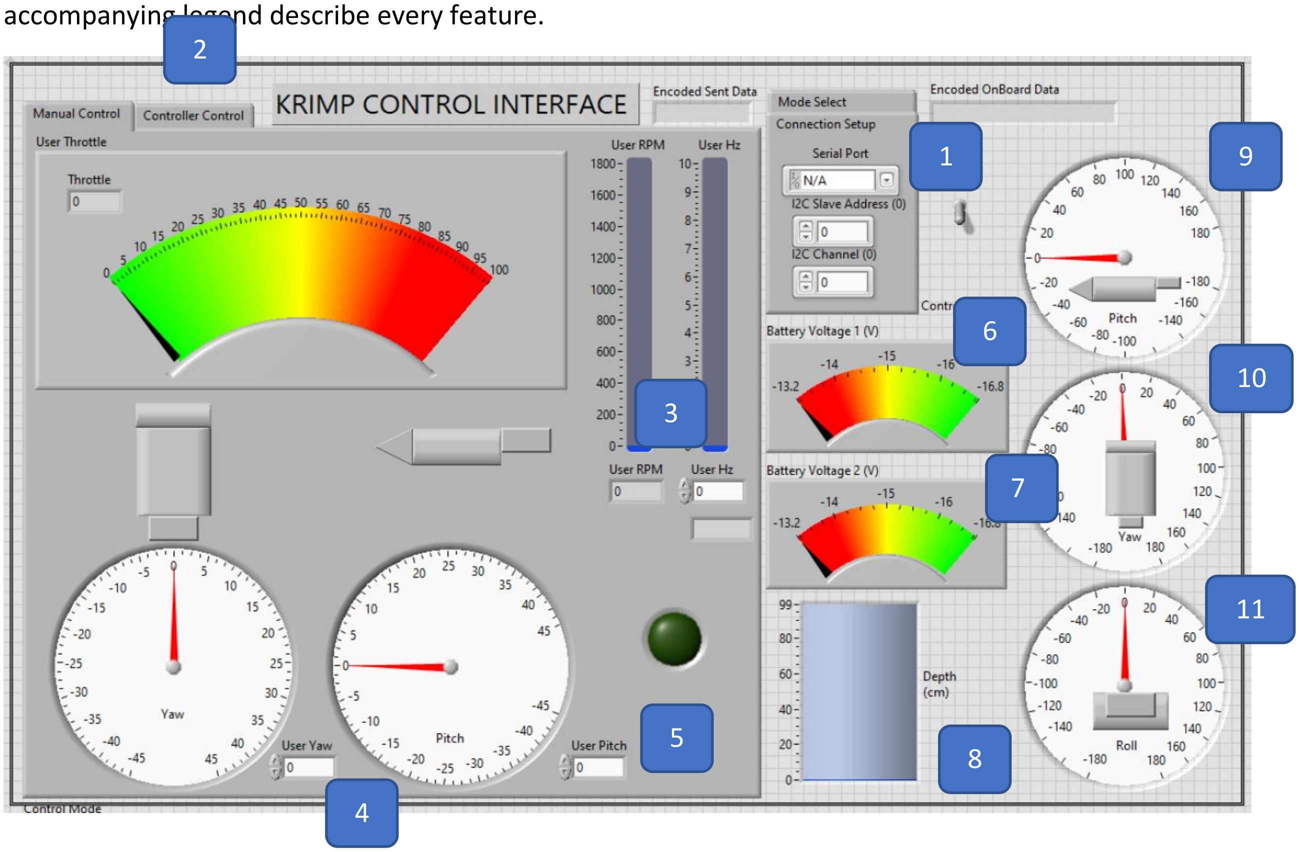
System Operation:

1. Vehicle taken to location of testing
2. Make sure area of operation is clear of hazards or non-research members
3. Gloves are equipped by operator(s)
4. Vehicle visually checked for any obvious tears breaks or other faults in body
5. Two or more people gently place the vehicle in the water and submerge it for several seconds (10 seconds recommended)
6. Remove from water and check for any water inside the machine
    a. If water is found, recheck the seal and repeat step 9-11 until no leaks are found
7. Place vehicle in the water and make sure the tether is not tangled or restricted in anyway

8. Check joystick and do several tests to make sure operation is running normal
    a. Rotate stick to check yaw, watch the tail
    b. Push stick forward and watch for symmetrical horizontal fin movement
    c. Push stick side to side and watch for opposite horizontal fin movement
    d. Push forward on throttle and watch for forward movement
9. Operators are clear to use as intended

Use of Hardware & Software

The LabVIEW GUI is the main communication with the KRIMP drone. The below figure and accompanying legend describe every feature.



Throttle: 0
Serial Port: N/A
I2C Slave Address (0): 0
I2C Channel (0): 0
User RPM: 0
User Hz: 0
User Yaw: 0
User Pitch: 0

1: Control Tabs: User selects serial port and Control Mode (I2C Slave Address = 9; I2C Channel = 0)

2: Input Tabs: Depending on user selection will allow for controller input or direct input

3: User input of throttle in Hz: (Surrounded by gauges of %Throttle and RPM of motor Shaft)

4: User Input and display of Yaw (Degrees)

5: User input and display of Pitch (Degrees)

6: Battery Voltage 1 (V)

7: Battery Voltage 2 (V)

8: Depth of Drone (cm)

9: Current Pitch (Degrees)

10: Current Yaw (Degrees)

11: Current Roll (Degrees)

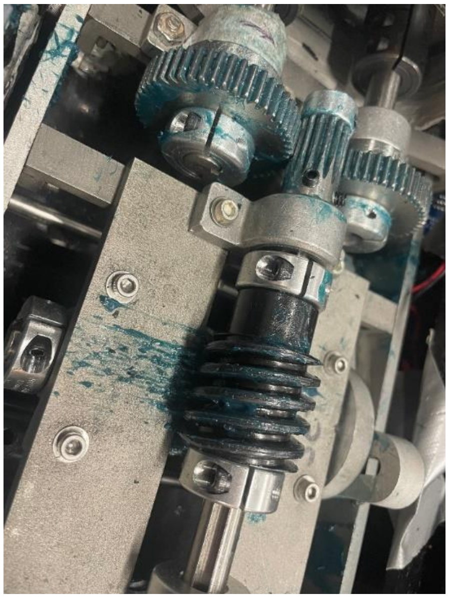
System Shutdown

1. Steer vehicle to point of retrieval
    a. It is recommended this point is somewhere close to land
2. Use two or more personal to lift out of the water
3. Allow vehicle several moments to have a preliminary drip dry (approximately 30 seconds to a minute)
4. Although not essential, it is recommended that operators wipe down the body of any residual water to ensure optimal working conditions in the future
    a. It is important to note that the motors generate a lot of heat. Depending on the amount of time used, it is advisable that the parts are given time to cool down. A general proportion of one to two minutes should be given to cool per minute of use.
5. Once dry, remove upper plate of vehicle
6. Flip both breakers to open position
7. Un-attach batteries from receivers
8. Reattach the upper plate and fasten
9. If planning to leave the drone dormant for a period longer than a week it is recommended to discharge the batteries using the setting shown below.
10. Allow for Bar30 depth sensor to completely dry before next use.

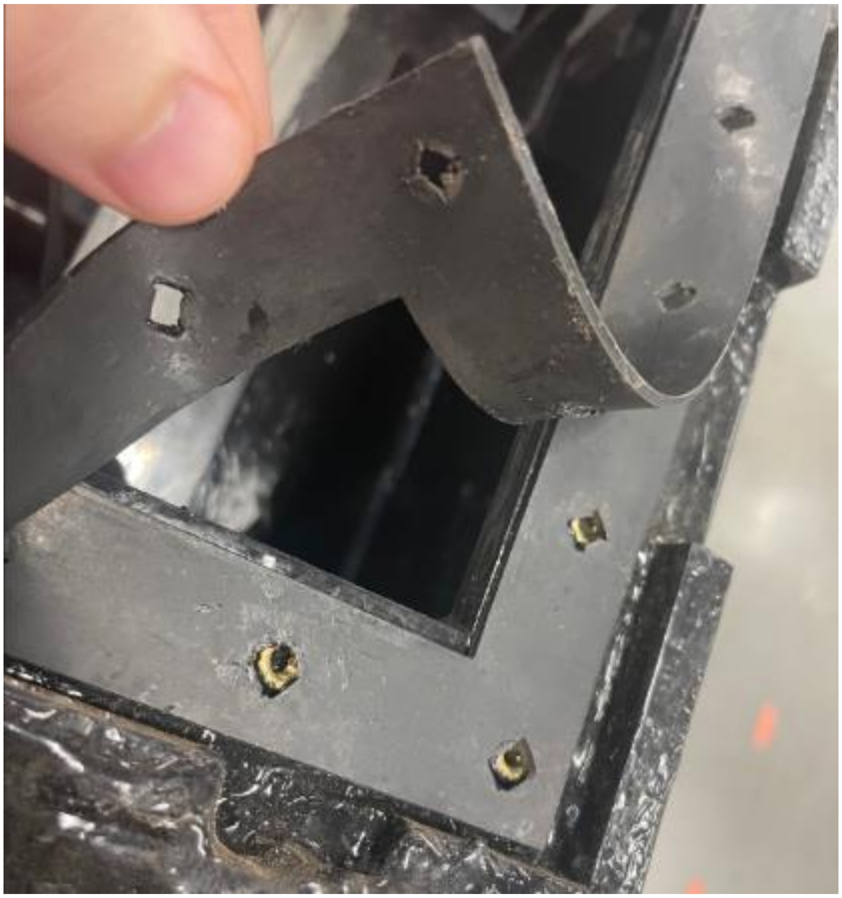
Maintenance Manual

1.) Remove batteries and place within fire retardant battery protection bag. Then connect the batteries to the battery charger and charge in balance charge mode. If preparing for storage, set the charger to discharge mode:

2.) Reapply marine grease to all mechanical components once every 10 running cycles. Ensure that grease is in contact with all mechanical meshing points:



3.) Clean gaskets and reapply Vaseline after every use to ensure that a watertight seal is created before every use.



Decommissioning Plan

1. If batteries are to be decommissioned alongside the drone, follow the steps below:

    a. Remove batteries from the drone
    b. Discharge the batteries following the steps given in the System Shutdown section
    c. Due to the environmentally friendly nature of Lipos, they can be thrown away in the standard garbage. Therefore, store batteries in fireproof bag or container filled with sand and dispose.
2. Remove and salvage any possible electrical components
3. Remove and salvage any possible mechanical components
4. Wearing proper PPE, break body into multiple sections to allow for easier disposal in the garbage.

REPORT BREAKDOWN OVERVIEW

Gabriel Webb –Derivation of Gear Train, Paddle Torque and deflection, Heat Analysis, and Frame Stress Analysis, Creation of Locomotion Test Bed, Testing of Design, and Team Management and Coordination. Design and manufacturing of Locomotion System & Body, Creation of Communication Protocol and LabVIEW GUI.

Grant Buchman – Electrical Design & Calculations, Risk Management, Paddle Calculations & Deflections, Introduction, Partial Body Analysis, Testing of Design, User Manual.

Michael Diaz – Detailed Design – Torque calculations, Heat Calculations, Logic, and Electronics. Motor Design, locomotion system, Testing of Design, Testing and Quality Plan, Project Plan, Assistance with Costs. Appendix B, Caption Corrections.

Anna Baird – Project Objective, Engineering Principles, Constraints and Considerations, Engineering Codes and Guidelines, Initial Concepts, Paddle Material Choice, Shaft and Collar Material Calculations, Assistance with Cooling Calculations, Testing of Design, Appendix A.

Robert Knight – Body Design, Assisted Gear Train Derivation, Optimizing of Budget, Cost Analysis, Locomotion Test Bed Design, Partial Body Analysis and FEA, Testing of Design.

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Team Signatures

Signature: Gabe Webb Date: 4/29/22

Signature: D. Michael Díaz Date: 04/29/2022

Signature: Grant Buchman Date: 04/29/2022

Signature: Anna Nicole Baird Date: 04/29/2022

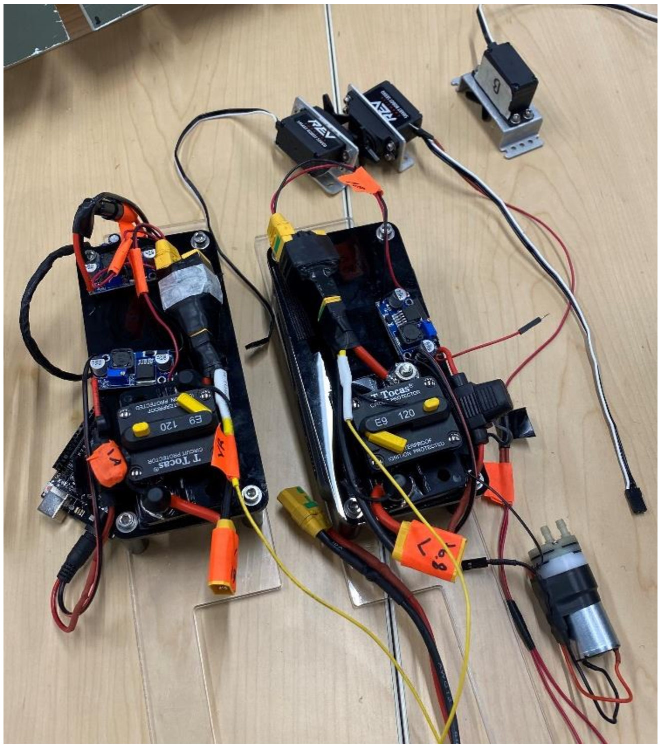
Signature: Robert Knight Date: 04/29/2022

APPENDIX A

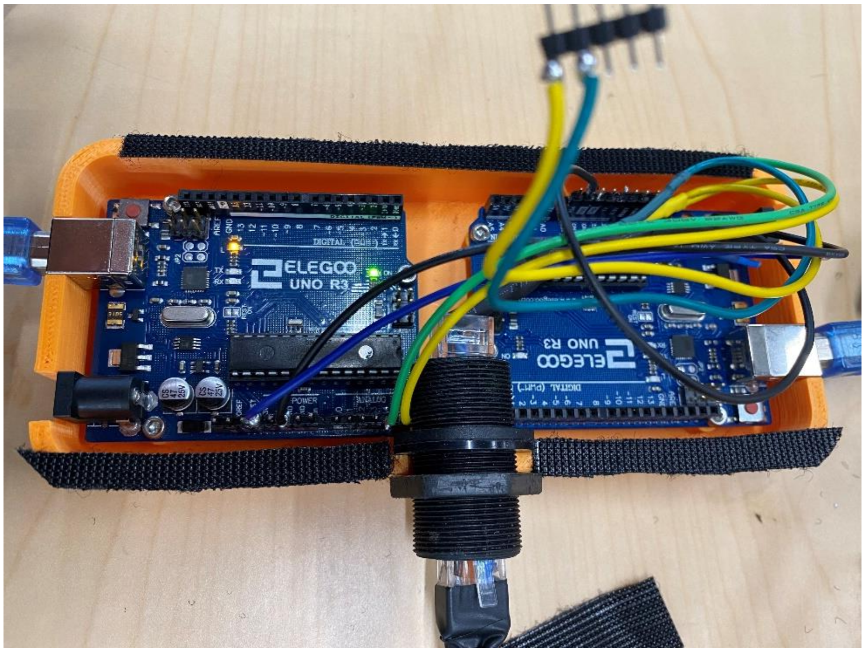
Images of the final design:

A 1. BLDC RevRobotics NEO Motor

A 2. Electronics Platforms

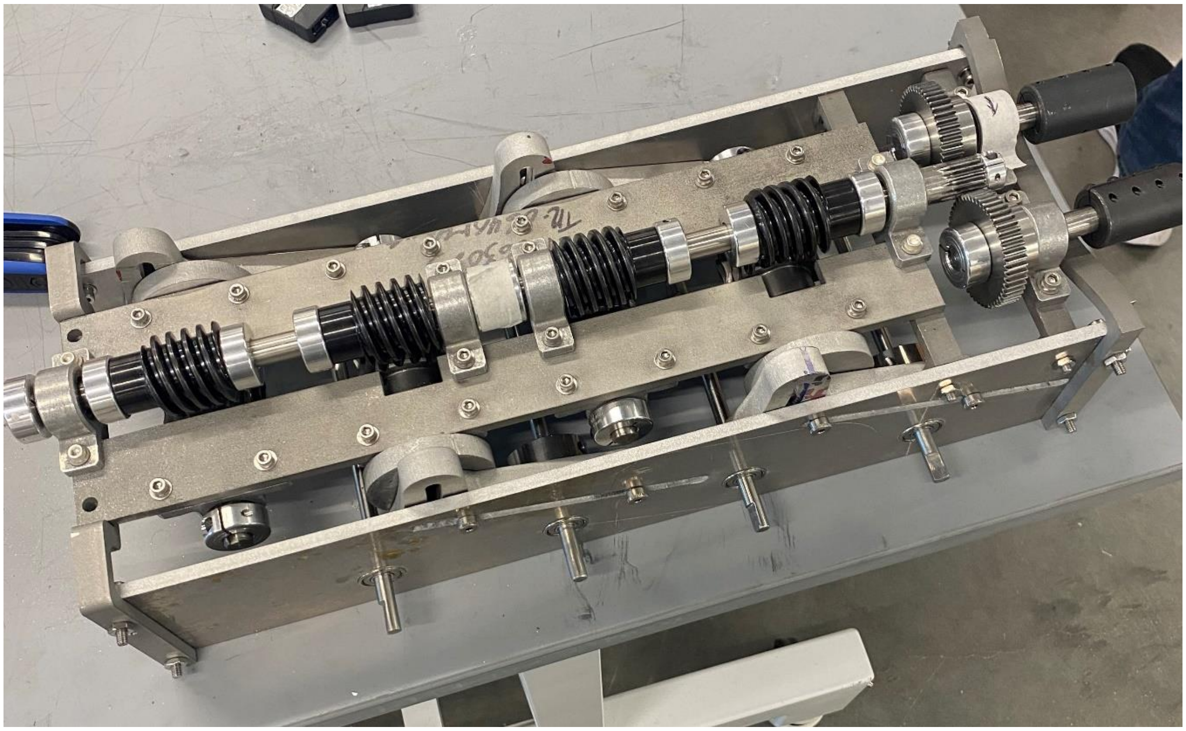


A 3. Arduino on-land computer box



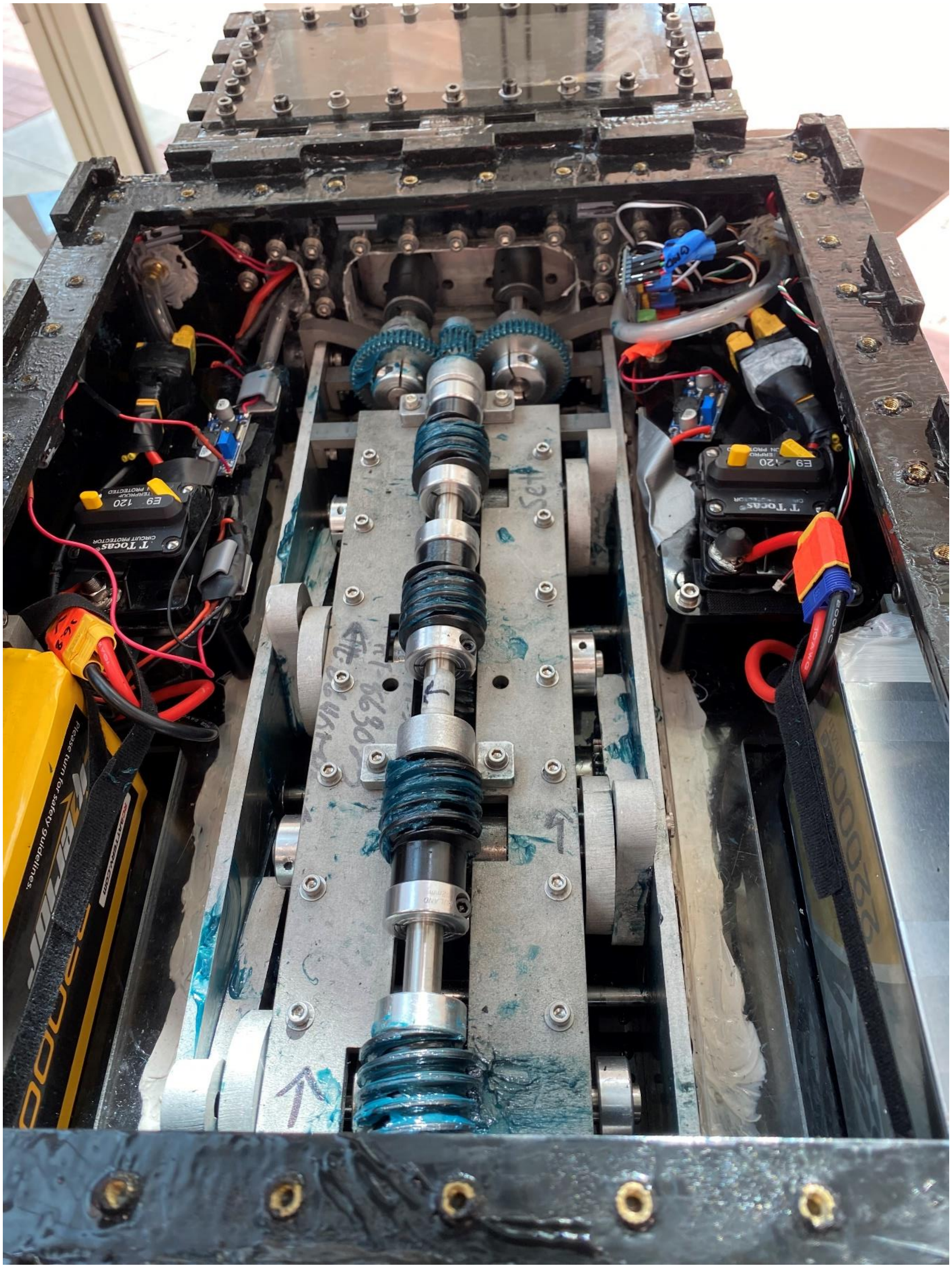
A 4. Tether Roll

A 5. Full Drive Train System

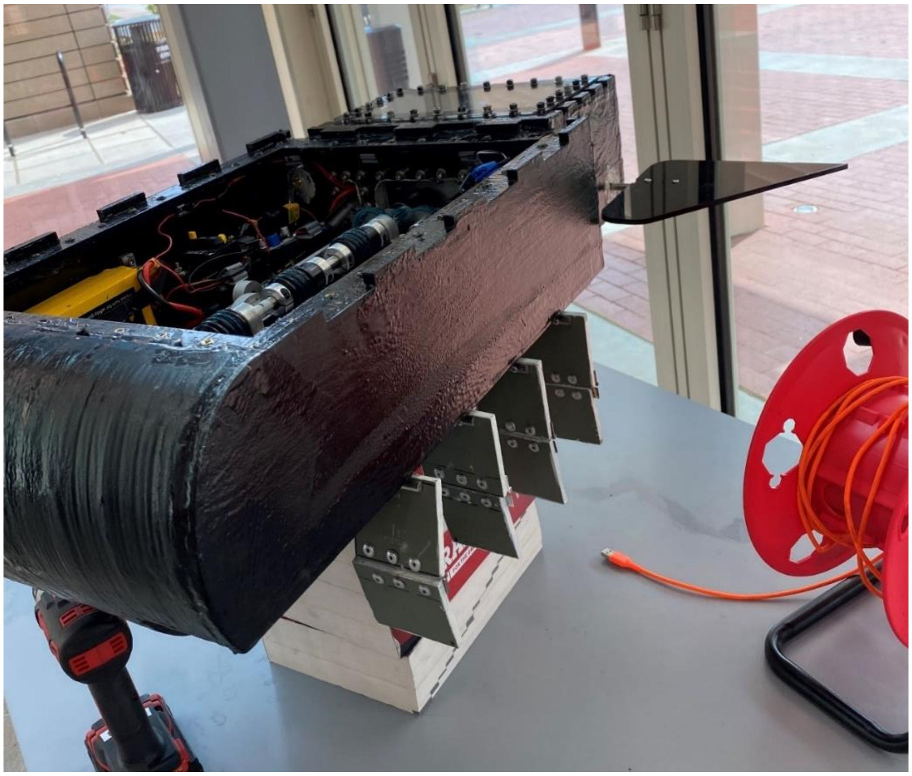


A 6. Fiberglass paddle design

A 7. Locomotion System and electronics in body

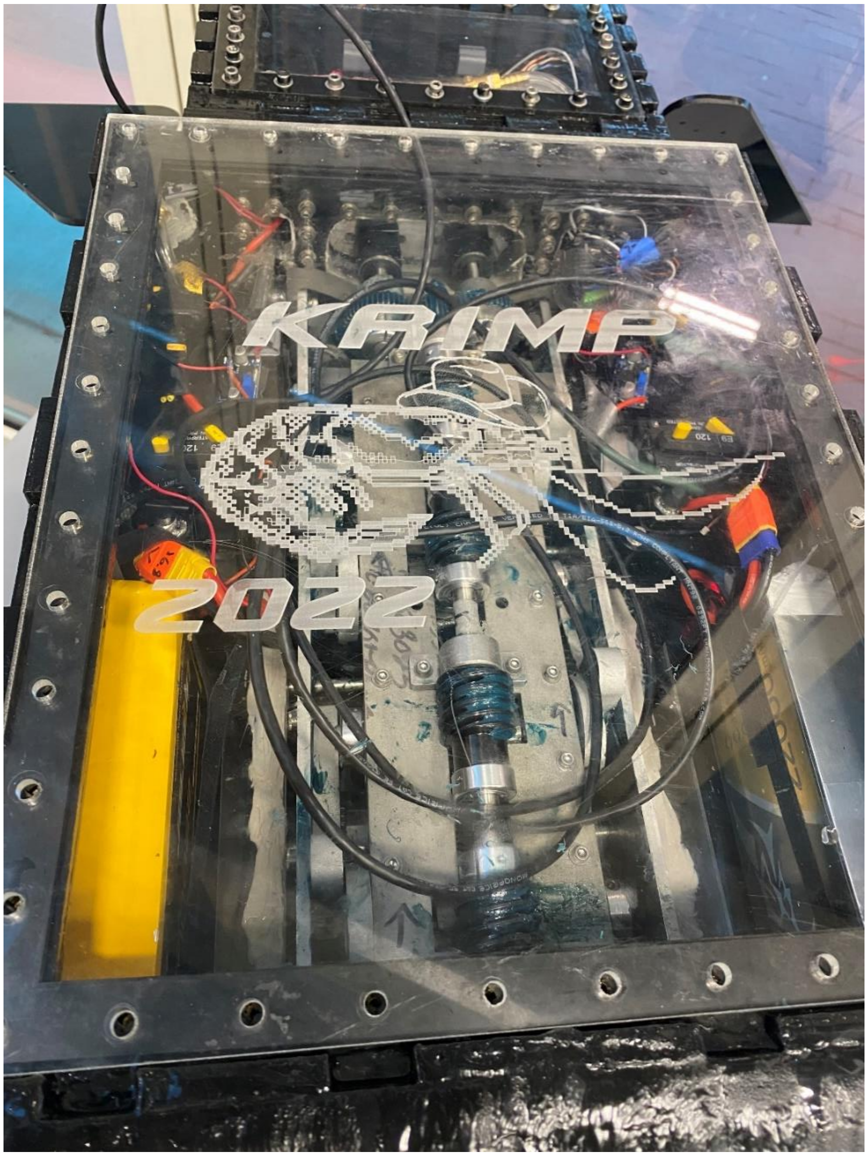


A 8. Full Built Design



A 9. Control Surfaces on back of body

A 10. Etched Lid body design

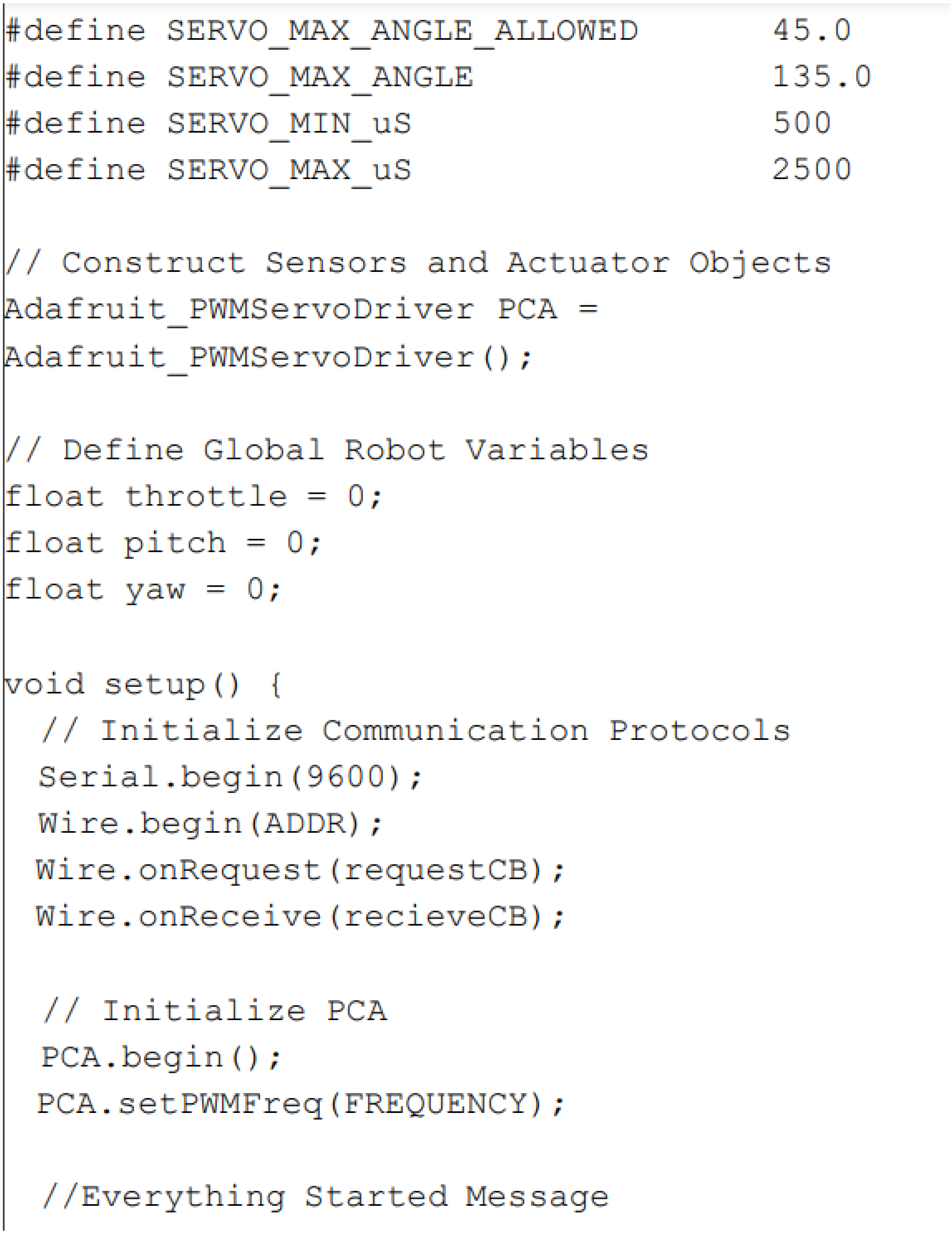


A 11. Milled waterproof bearing

A 12. Marine Grease used for lubrication of locomotion system

A13: C++ code for Slave Arduino:

```
//Libraries
#include <Wire.h>
#include <Adafruit_PWMServoDriver.h>

// Define I2C Communication Parameters
#define ADDR                                 9
#define PACKAGE_SIZE                         24
String messageout =
"D000E000F000G000H000I000";

// Define PCA Parameters
#define FREQUENCY                            100.0
#define PULSE_BITS                           4096
const float FACTOR = (1000000.
0)/(FREQUENCY*PULSE_BITS);

// Define Motor Parameters
#define MOTOR_A                              8
#define MOTOR_B                              9
#define MOTOR_MAX_uS                         2000
#define MOTOR_MIN_uS                         1575

// Define Servo Parameters
#define SERVO_1                              0
#define SERVO_2                              1
#define SERVO_3                              4
```



```
#define SERVO_MAX_ANGLE_ALLOWED      45.0
#define SERVO_MAX_ANGLE              135.0
#define SERVO_MIN_uS                 500
#define SERVO_MAX_uS                 2500

// Construct Sensors and Actuator Objects
Adafruit_PWMServoDriver PCA =
Adafruit_PWMServoDriver();

// Define Global Robot Variables
float throttle = 0;
float pitch = 0;
float yaw = 0;

void setup() {
  // Initialize Communication Protocols
  Serial.begin(9600);
  Wire.begin(ADDR);
  Wire.onRequest(requestCB);
  Wire.onReceive(recieveCB);

  // Initialize PCA
  PCA.begin();
  PCA.setPWMFreq(FREQUENCY);

  //Everything Started Message
```

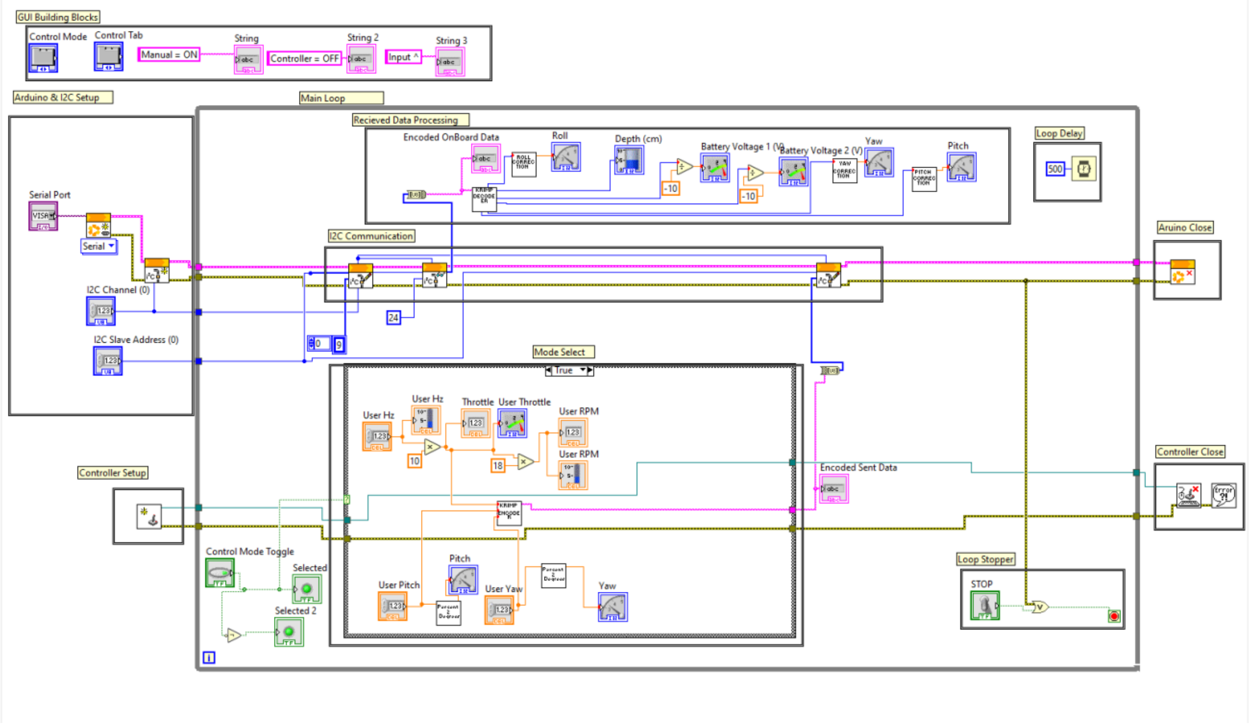
```
  Serial.println("Everything Initialized");
  delay(2000);
}

void loop() {

  driveMotor(MOTOR_A,throttle);
  setServo(SERVO_1,pitch,false);
  setServo(SERVO_3,pitch,true);
  setServo(SERVO_2,yaw,false);
  delay(100);
}

void setServo(int servoPin, float percentage,
bool flipped){
  percentage = max(0,min(100,percentage))/100.
0;
  float angle =
(2*SERVO_MAX_ANGLE_ALLOWED)*percentage
-SERVO_MAX_ANGLE_ALLOWED;
  int microSeconds =
map(angle,-SERVO_MAX_ANGLE,SERVO_MAX_ANGLE,SER
VO_MIN_uS,SERVO_MAX_uS);
  if(flipped){microSeconds =
map(angle,-SERVO_MAX_ANGLE,SERVO_MAX_ANGLE,SER
VO_MAX_uS,SERVO_MIN_uS);}
```

```
  int bits = calcPWMBits(microSeconds);
  PCA.setPWM(servoPin,0,bits);
}

void driveMotor(int motorPin, float
percentage){
  percentage = max(0,min(100,percentage))/100.
0;
  int bits =
calcPWMBits(calcMicroSeconds(percentage,MOTOR_
MIN_uS,MOTOR_MAX_uS));
  PCA.setPWM(motorPin, 0, bits);
}

float calcMicroSeconds(float percentage, int
min_uS, int max_uS){
  float microSeconds =
(max_uS-min_uS)*percentage + min_uS;
  //float microSeconds =
(min_uS-max_uS)*percentage + max_uS;
  return microSeconds;
}

int calcPWMBits(float microSeconds){
  float bits = microSeconds/FACTOR;
  return (int)bits;
```

```
}

void Decoder(String msg) {
  if (msg != "-39") {
      throttle = msg.substring(1,4).toInt();
      pitch = msg.substring(5,8).toInt();
      yaw = msg.substring(9).toInt();
    }
}

void requestCB(){
  byte response[PACKAGE_SIZE];
  for (byte i=0;i<PACKAGE_SIZE;i++)
{response[i] = (byte)messageout.charAt(i);}
 Wire.write(response,sizeof(response));
}

void recieveCB(){
  String message = "";
  byte x;
  while(Wire.available()){
    x = Wire.read();
    if (x == 65) message += "A";
    else if (x == 66) message += "B";
    else if (x == 67) message += "C";
    else message += map(x, 48, 57, 0, 9);
```

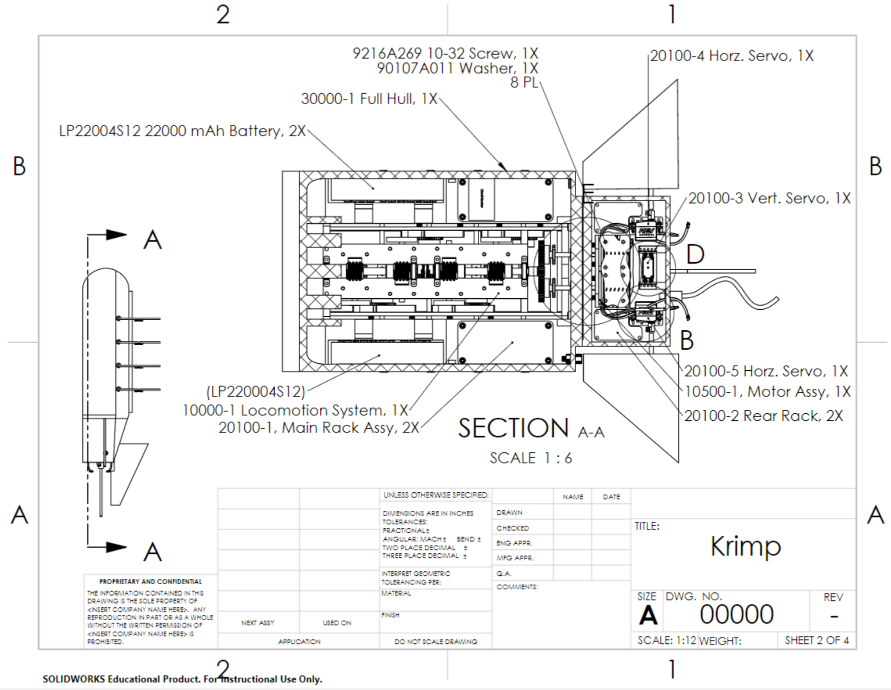
```
  }
  Decoder(message);      //Calls decoder
function to convert from a string command to
integer values
}
```

A14: LabVIEW: GUI Block diagram

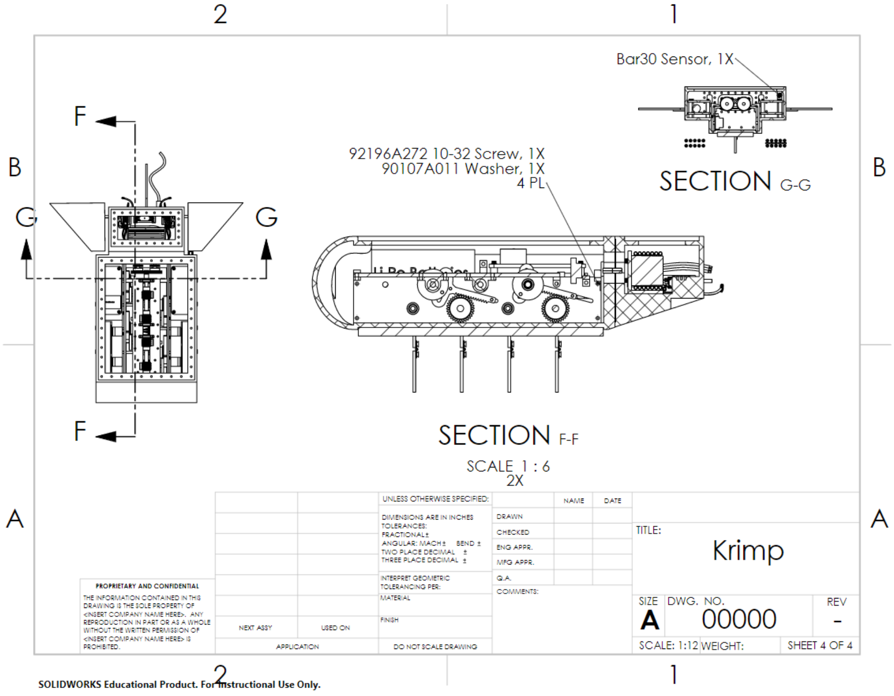


Appendix B – CAD Drawings

Body

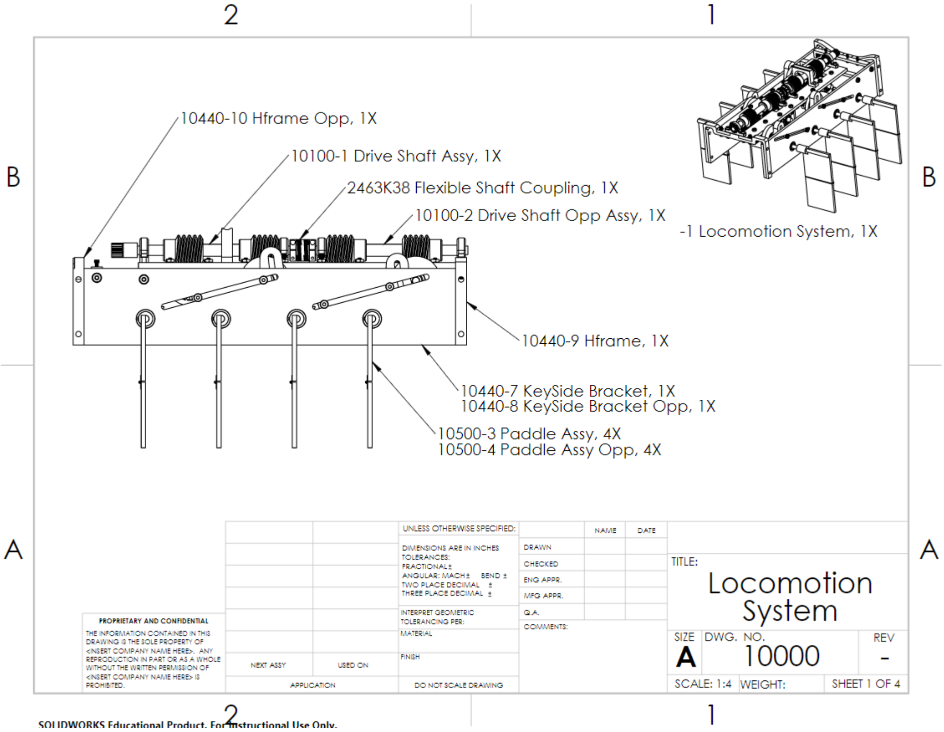


B 1. Engineering drawing of full body – Top

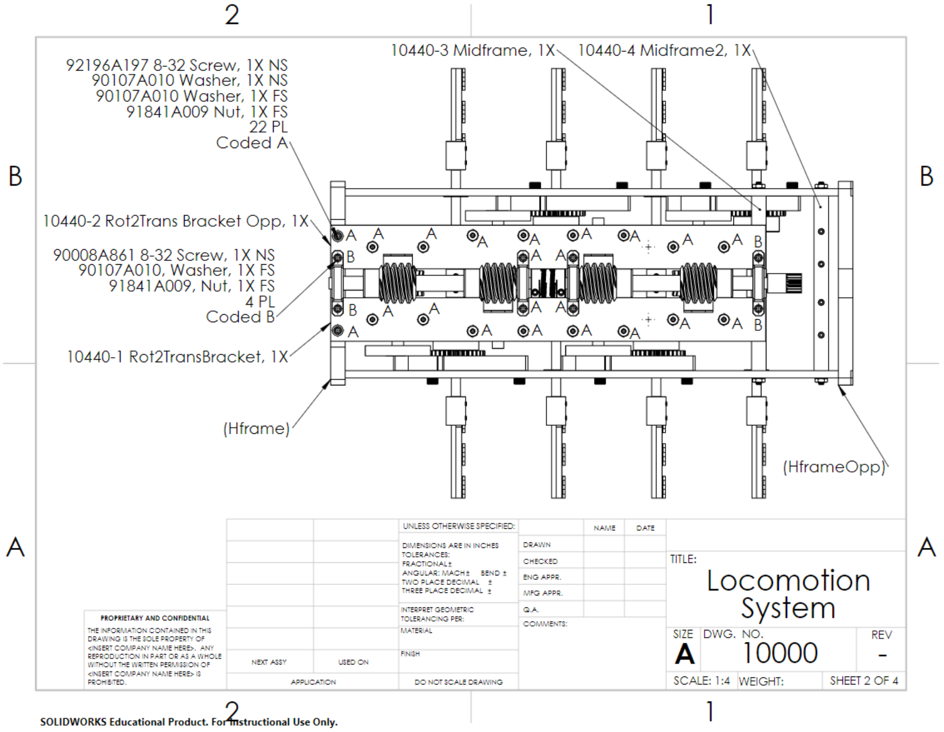


B 2. Engineering drawing of full body – Side

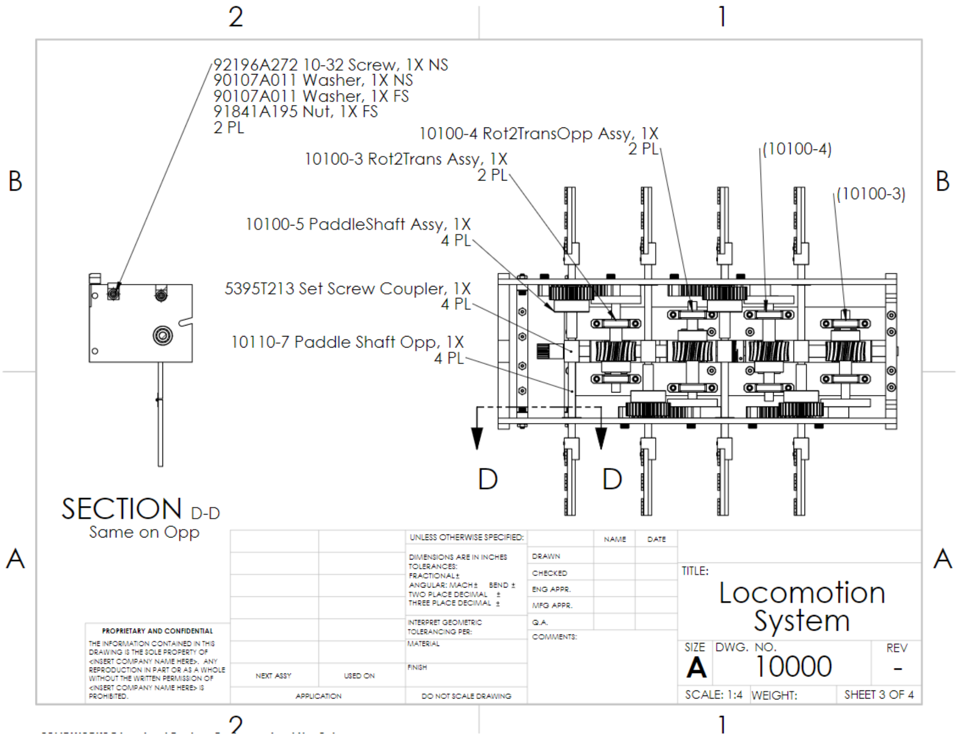
Locomotion



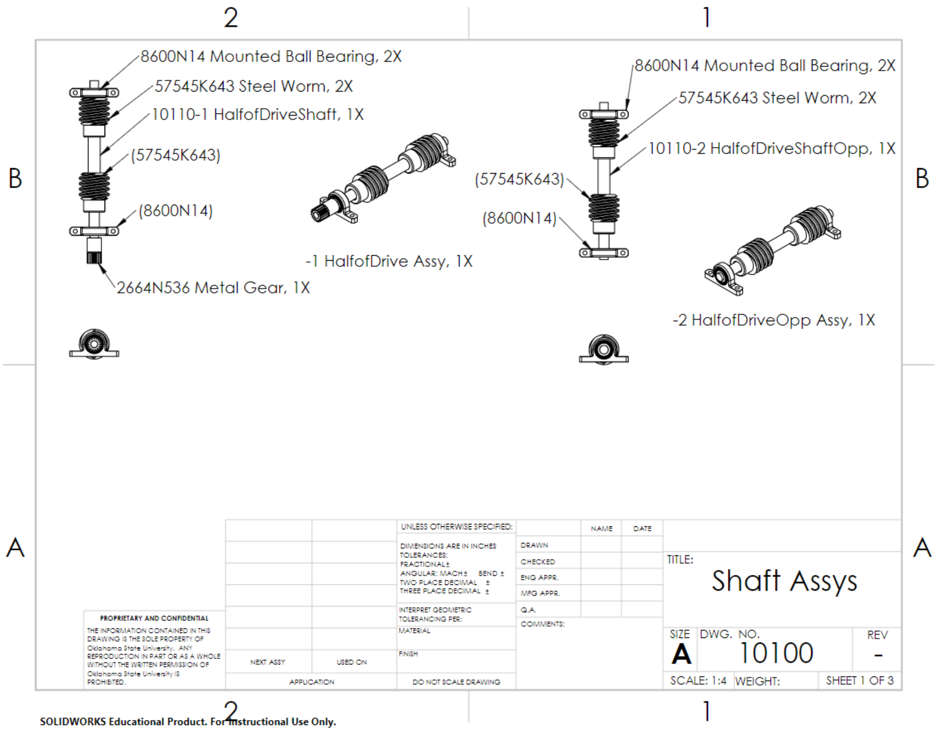
B 3. Locomotion – Side



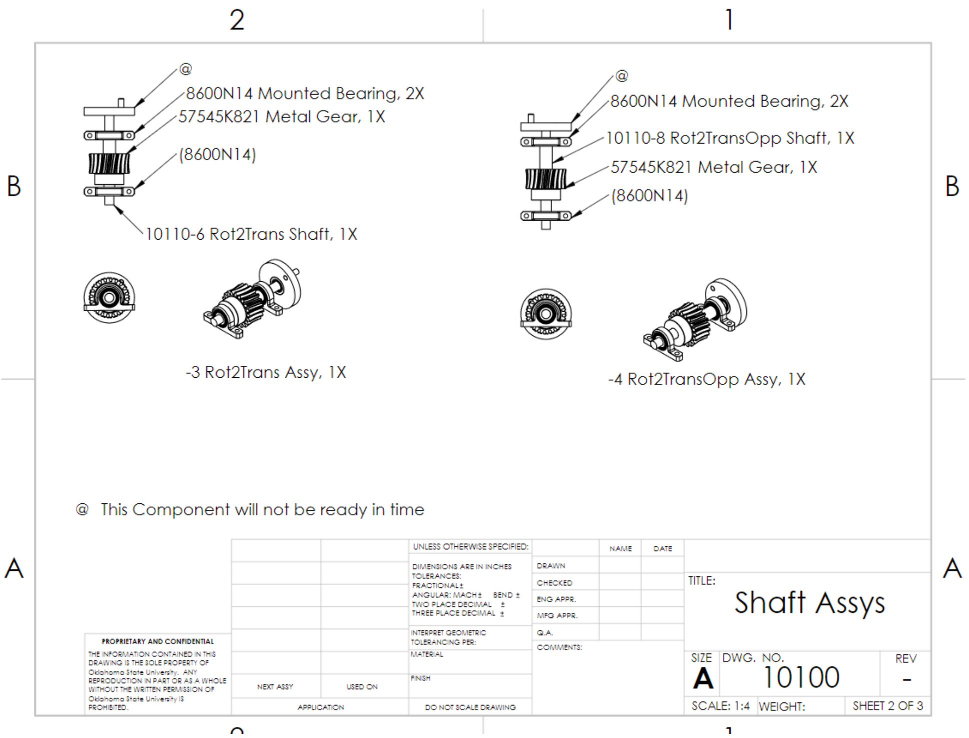
B 4. Locomotion - Top



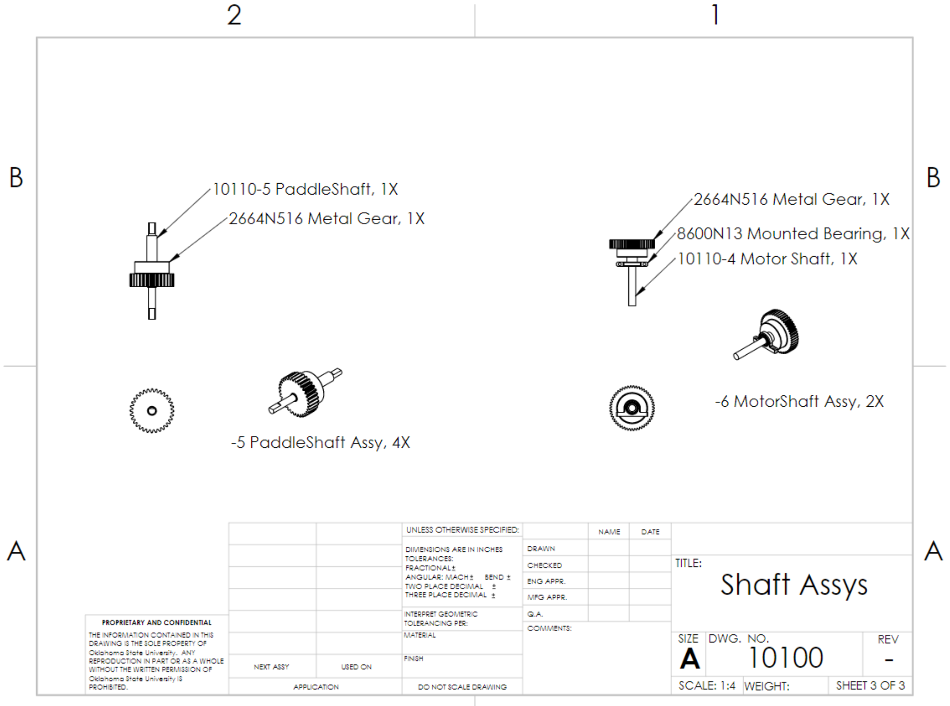
B 5. Locomotion – Bottom



B 6. Central Worm Shaft



B 7. Rot2Trans Shaft



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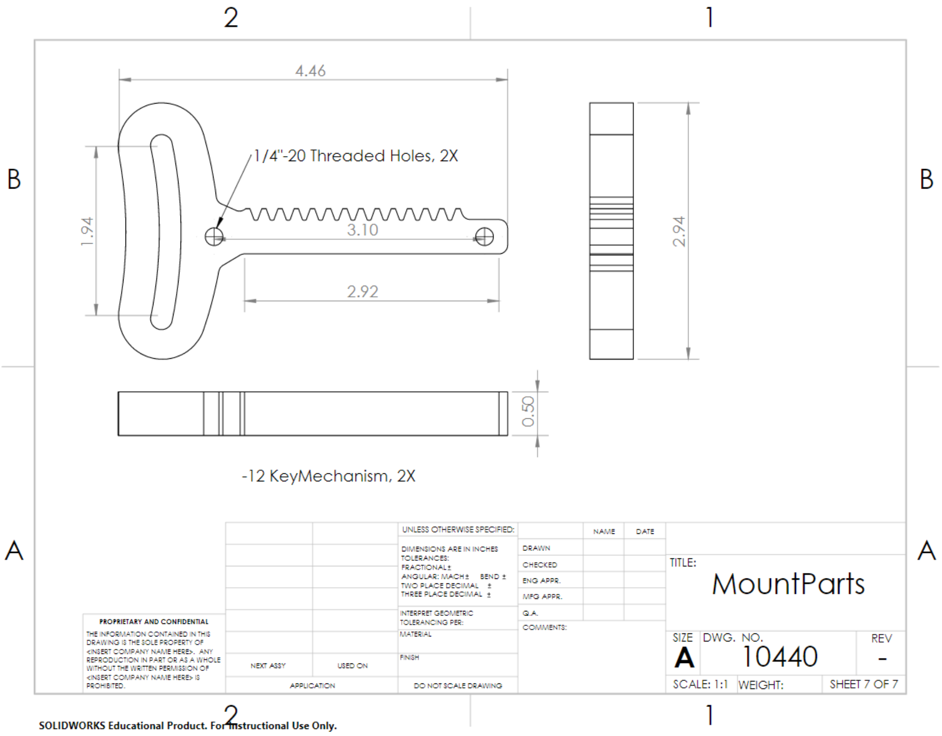
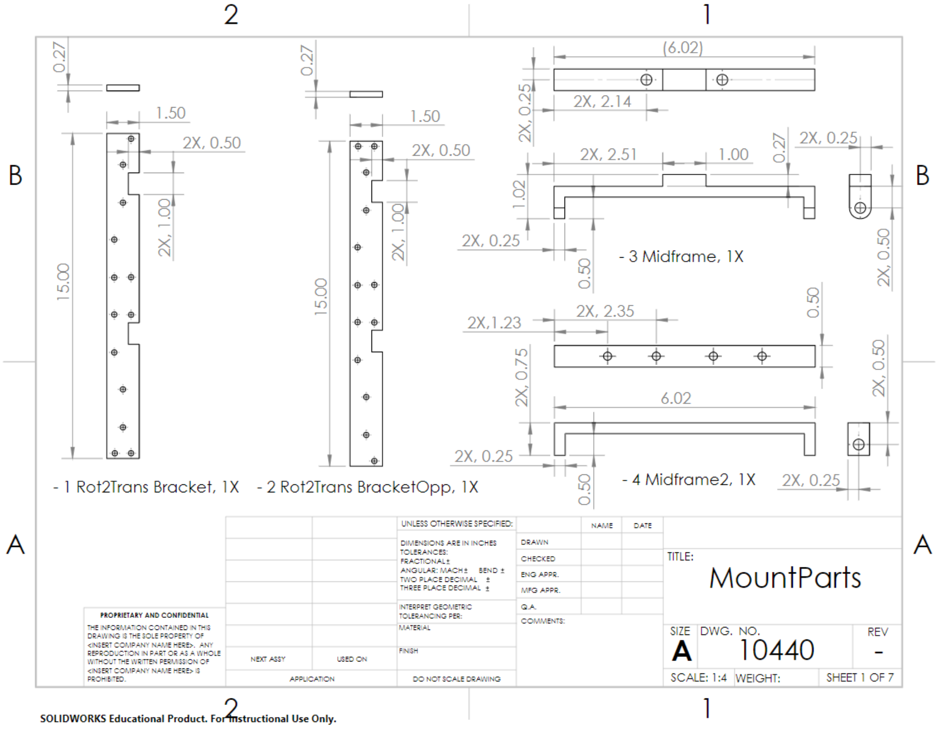
B 8. Paddle Shaft

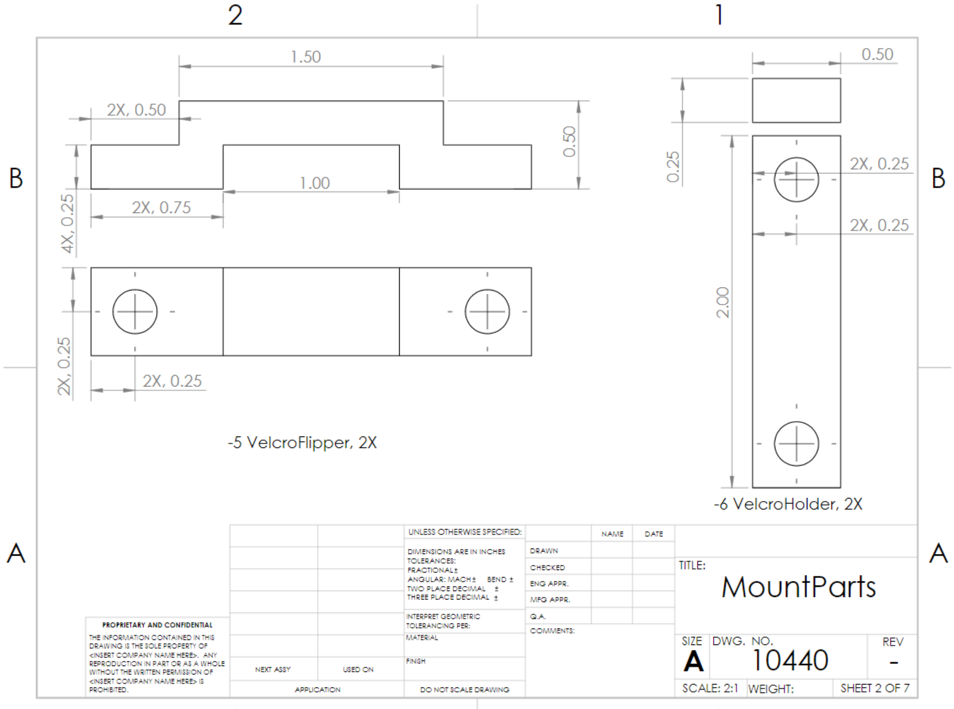


B 9. The Key

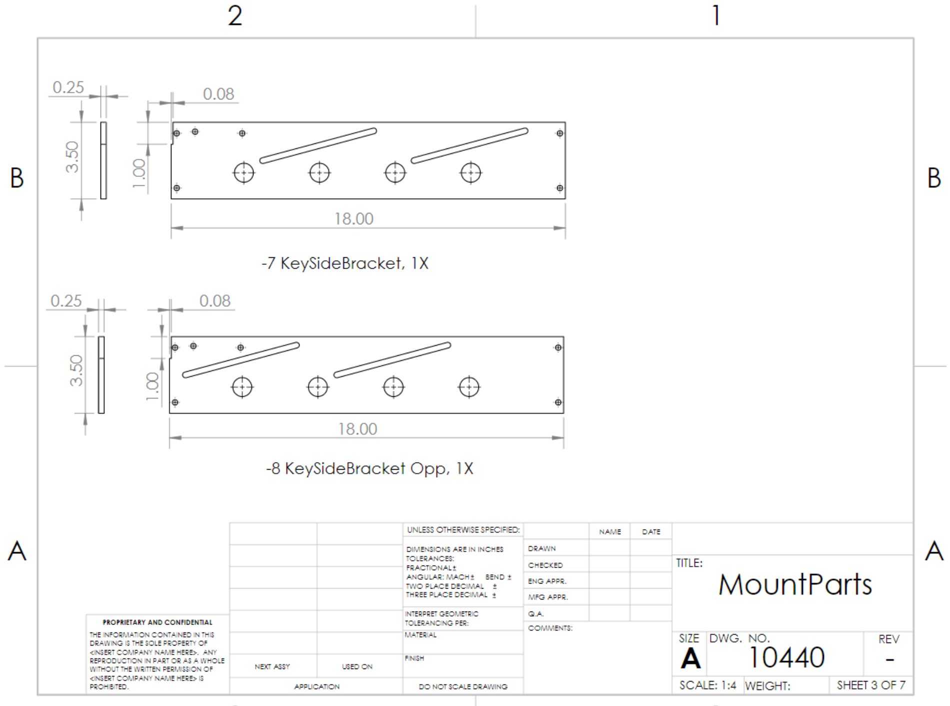
Locomotion Mount



B 10. Rot2Trans Bracket



B 11. Battery Velcro Securer



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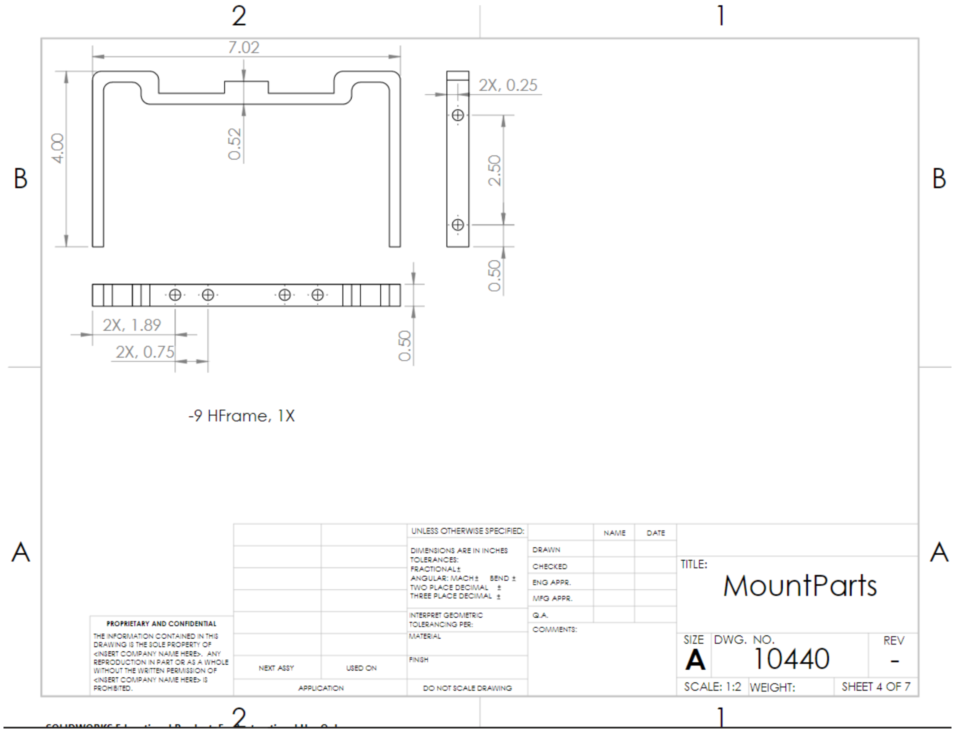
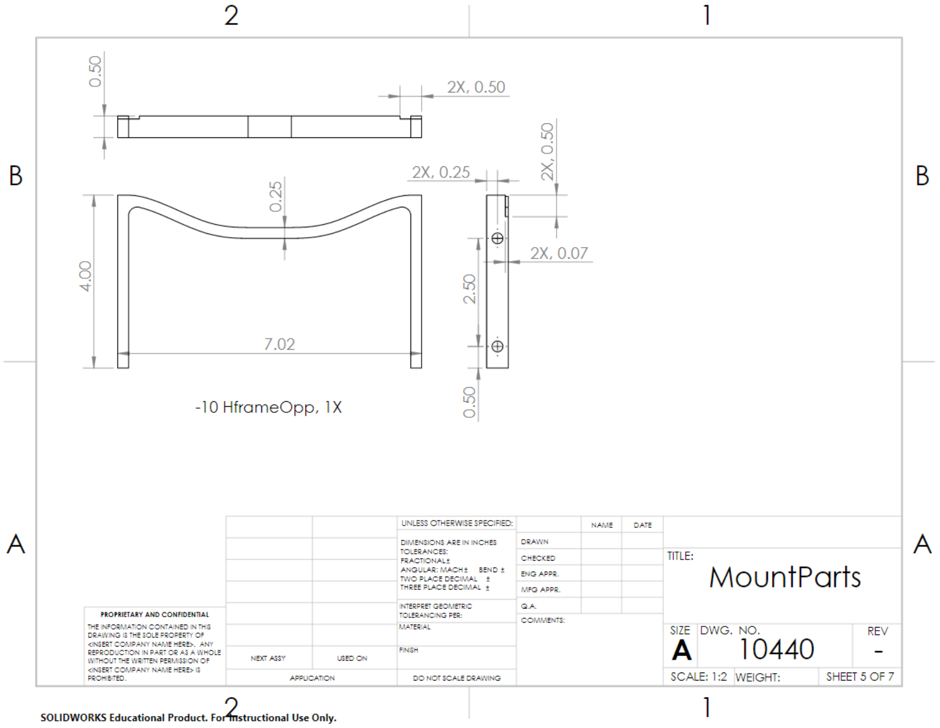
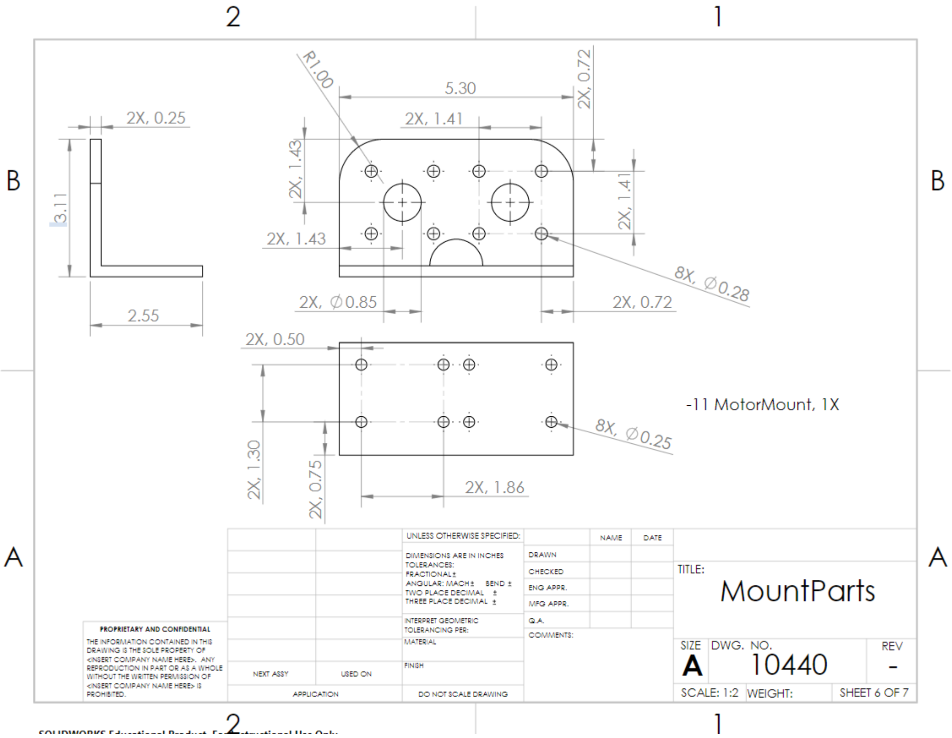
B 12. Key Side Bracket



B 13. H-Frame

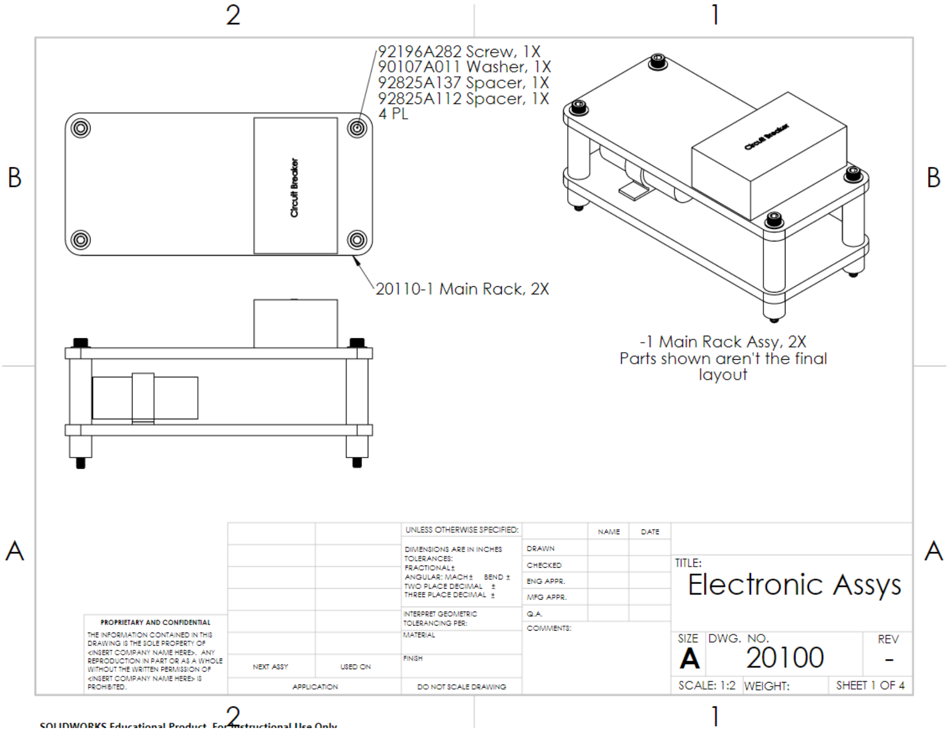


B 14. H-Frame Opposite



B 15. Motor Mount

Electrical



B 16. Electronics Rack